Productivity and Utilisation of Winch-Assist Harvesting Systems: Case Studies in New Zealand and Canada

A thesis submitted in partial fulfilment of the Master of Forestry Science

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# Abstract

Winch-assist technology is now a well-established system to support forest harvesting on steep slopes. The winch-assist harvesting system is a combination of the winch-assist machine (WAM) at the top of the slope that allows steep slope machines (SSM) to manoeuvre down slopes. The SSM is attached to a winch rope from the WAM to carry out tasks such as mechanised felling. Winch-assist harvesting systems are expensive and little is known about their productivity and utilisation rates, or the factors that affect this. This research aimed to improve knowledge of winch-assist harvesting systems in terms of productivity and utilisation through six case studies in New Zealand and Canada.

Two to five days of continuous operational data were collected at each of the six case studies. Productivity of the winch-assist harvesting system was determined by measuring the volume harvested in the time that the SSM was carrying out its primary tasks of felling, bunching, moving between trees, and brushing. The Utilisation is then the ratio of the productive machine time (PMH) as a percentage of the total scheduled machine time (SMH). The difference between PMH and SMH will be the system working on tasks other that its primary tasks, or in delay. Delay time was further defined as operational, mechanical, or personal. Productivity per SMH is then the product of the m^3/PMH and utilisation (%) and calculated using the product of the utilisation rate and the volume harvested per PMH.

The average productivity recorded through the six case studies was 61m^3/PMH, ranging from 34m^3/PMH to 102m^3/PMH. The site with the lowest productivity was a result of small piece size and while the site with the largest productivity was a result of large piece size and long even slopes leading to less WAM relocations.

The average winch-assist harvesting system utilisation recorded in these six case studies was 52%, ranging from 25% to 63%. Delays and shovelling were common, accounting for 48% of the total recorded time (delay 37%, shovelling 11%). Operational delays summed 69% of total delay time; these delays included relocating the WAM, moving setting, setting up and planning, line handling, diesel activities, radio communication and assisting with other operations. Short corridor lengths meant increased WAM relocations and had the largest relation to operational delay. Mechanical delays, when the machine was not able to work due to repair or maintenance, accounted for 17% of total delays. Mechanical delays included greasing the machines, chain and bar issues and general maintenance. Thick undergrowth and small trees within the forest stand had a large impact on chain and bar issues. Personal delays involving the operator taking a break were 14% of total delays.

As a result, average productivity per SMH was 33m^3/SMH, and ranged from 11m^3/SMH to 58m^3/SMH in the six case studies. This highlights the effect of low utilisation in that it almost halves the productivity potential, but it is important to understand the reasons for delays, many of which are unavoidable.

Winch-assist supported shovelling, while being considered an operational delay in this study because it limits the SSM in its felling task, was a common practice through the six case studies. Shovelling is in support of the extraction activity, for example moving stems to a visible location for cable extraction or to an area able to be accessed by ground based extraction machines. So while this effectively increases the felling cost, it increases the productivity of the next process in the harvesting system.

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Achievements

In addition to my Masters Thesis project, I was able to contribute and participate in the following professional activities:

New Zealand:

- Assistant teacher for FORE 422 (Forest Harvest Planning) at the University of Canterbury
- Assist with labs and field trips for FORE 423 (Forest Road Planning) at the University of Canterbury
- Support a week-long Winch-Assist Skidder Extraction Time Study in Gisborne
- Co-author of Forest Growers Research Report:
    - *Productivity and utilisation of winch-assist machines: case studies in New Zealand and Canada*
- Attended the Safe Tree Conference in Christchurch
- Attended the two-day Harvest Tech Conference in Rotorua
- Attended the Winch-Assist Expert Panel Workshop and Industry Practice Review in Nelson
- Assist Rien Visser and Hunter Harrill with a week-long Forest Engineering Development Course at the University of Canterbury (RoadENG, Harvest Planning, Cable Yarding Configurations)
- Assist Rien Visser with five Winch-Assist Workshops:
    - Christchurch
    - Timaru
    - Nelson
    - Whanagrei
    - Kaitaia

North America:

- Visiting International Research Student at the University of British Columbia (4 months)
    - Internship at FPInnovations, British Columbia
- Guest lecture at the University of British Columbia on New Zealand Forestry
- Co-author of two FPInnovations Info Notes:
    - *Assessment of Falcon Forestry Equipment Winch-Assist in British Columbia's Kelowna Region*
    - *Remote Operated Bulldozer Assessment in British Columbia. Armstrong Region*
- Attended the Forest Operation Safety Conference in Nanaimo, British Columbia
- Attended the Rayonier annual Safety Conference in Ocean shores, WA, USA
- Assist Rien Visser with two Winch-Assist Workshops:
    - Forks, WA, USA
    - Hoquium, WA, USA

Europe:

- Preparation at Boku University, Austria for the Formec Conference (one week)
- Guest lecture at Boku University, Austria on New Zealand Forestry
- Attended the three-day Formec Conference in Sopron, Hungary
    - Presented thesis topic
- Attended the Austrofoma Machine Exhibition in Forchtenstein, Austria

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1. Introduction

Forestry is a significant industry in New Zealand and Canada, contributing 3 percent of New Zealand's Gross Domestic Product (Ministry for Primary Industries, 2018) and 1.2 percent of Canada's (Government of Canada, 2016). In New Zealand, plantation forestry covers 1,717,700 hectares or 6.4 percent of land area, excluding harvest area awaiting replanting. Currently, 49.900 hectares are harvested annually with a value of $4.75 billion and are the third-largest export industry in the country (Forest Owners Association, 2016). Because of the scale, research is continually being carried out to optimize systems and create a more productive and safer environment.

Winch-assist allows steep slope machines (SSM) to manoeuvre down slopes with the security of a winch from a WAM at the top of the slope. Winches can be integrated into the SSM, although this is not common in New Zealand. New Zealand first introduced winch-assist machines in 2006 and manufacturers now have 120 spread throughout the country and have exported around 130 as of July 2019 (Winch-Assist Expert Panel and Industry Practice Review, 2019). Of the 120 machines in NZ, 45 are EMS TractionLine; a dual winch excavator system. 35 are DC Equipment Falcon Forestry winch-assist; single winch excavator system. 18 are Remote Operated Bulldozers (ROB); which is a dual winch system with operating alarms. Seven are Waka Engineering winch-assist; a single winch excavator system. Three are ClimbMAX steep slope harvesters, which is a single winch integrated into a feller-buncher track frame. The remaining twelve machines are NZ developed systems only operating within NZ.

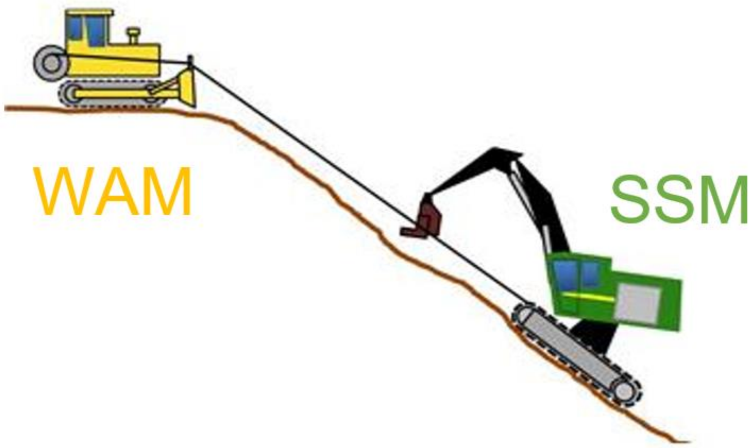

Figure 1. A typical winch-assisted harvest system, whereby the winch-assist machine (WAM) is powering the winch at the top, and the steep slope machine (SSM) in this case is an excavator based felling machine.

Forests commonly occupy steep, remote and erosion-prone land that is not suitable for farming. A large area of forest is becoming available to harvest as a result of sheep farm conversions in the late 1980s and early 1990s during a period of increased planting (New Zealand Institute of Economic Research, 2017). Some of these forests may be economically unviable to harvest due to steep terrain, extensive infrastructure requirements, small tree size, and where harvest and transport costs exceed the market value of the trees (Ministry for Primary Industries, 2014). The increased availability of this wood source will see a trend toward steeper and more difficult forest areas suited to winch-assist harvesting.

Steep terrain harvesting is also projected to increase in Canada. Timber on steep slopes are an increasingly crucial future fiber source as large scale disturbances caused by insects and wildfires have put pressure on traditional forest fibre sources and are forcing the industry to direct operations into previously unutilized and marginalized stands (Amishev & Dyson, 2018). Specifically, this is a result of the Mountain Pine Beetle attack, that started in the 1990s and has resulted in the mortality of 50 percent of the total volume of commercial Lodgepole pine (Pinus contorta) in British Columbia. Currently, an outbreak covers over 16.3 million ha of British Columbia and Alberta in Western Canada (De la Giroday et al., 2011). Furthermore, the Government's initiative to slow the beetles' spread is to harves affected stands before the economic value of the wood is lost or diminished (Government of Canada, 2018). A study carried out by De la Giroday and others (2011) found that Mountain Pine beetle (Dendroctonus ponderosae Hopkin) is primarily established in canyons and valleys, before moving into more open-sloped areas. Southwestern slopes of mid-slope ridges and small hills, southwest facing open slopes, and valleys that run in a northeast-southwest cardinal direction were positively associated with higher intensities of infestation. The need to increase harvesting on steep slopes has resulted in an increased interest into winch-assist harvesting systems in Western Canada. Today more than 50 winch-assist machines from a range of different manufacturers are working in Western Canada.

Previous studies on winch-assist productivity and utilisation studies provide widely differing outcomes. Amishev & Dyson; (2018) recorded a productivity of 42.8 m^3/PMH while Malietoa (2016) from three different winch-assist operations, recorded productivities of; 79.6m^3/PMH, 99.5m^3/PMH, and 109m^3/PMH. Results from a five-month utilisation study in New Zealand indicated a winch-assist utilisation at 57%. Another survey of 12 winch-assist machine owners found a low utilisation of 45% (Harrill, Reriti, & Visser, 2018).

The method of work-study undertaken was a detailed time study taking into account several variables. Some of the critical variables included in the analysis are; slope, piece size, operator skill, machine size, working method/machine brand, terrain (rock outcrops, wet soils), stand condition (mortality, wind throw). For each operation, three to five days was required in the field to provide sufficient data for analysis.

Winch-assist machines require large amounts of time when shifting and relocating on the slope (Harril, Reriti, & Visser, 2018). The utilisation rate is expected to differ depending on the ease of access on, off, and around the working area. The sampling procedures will be assessed and stage-gated after the first site visit to determine if adjustments to the methodology are required.

Increasing mechanisation results in higher operational costs. With the already tight profit margin of harvesting on steep terrain, increased machinery costs and the likely fell of the NZ dollar (driving up already inflated machine costs), profitability on steep terrain becomes progressively more sensitive with increasing mechanisation (Raymond, 2012). Information on steep slope harvesting productivity and cost is limited. This research project will provide a basis for what winch-assist harvesting systems can achieve.

The focus of this research project will aim to give forest engineers, forest managers, and contractors a guide to the productivity of winch-assist harvesting systems and the factors that affect it. Productivity and relating factors will be assessed, identifying effective work methods, and identifying suitable working conditions. Operations identified will be treated individually rather than creating comparisons between each operation. It is assumed that the best knowledge gain will be from assessing operations with different productivity and relating the various site factors such as: landing and setting difficulty and size of trees. In summary, carrying out this project will provide a gauge on what works well in a winch-assist operation.

2. Review of Literature

Winch-assist harvesting machines are referred to by many different names throughout the world including cable-assist, tethered or bungee slinger. Winch-assist machinery for forest operations have been commercially available in Europe since the 1990s (Sebulke, 2011), with a number of different companies offering cable winch products that are either integrated onto the machine or a separate attachment (Sutherland, 2012). Initially, they were mainly used on forwarders (e.g., Bombosch et al., 2003, Wratschko 2006), but there are now numerous commercial options to extend that technology to harvesters (Sebulke, 2011). Winch-assist systems can significantly increase the ability to operate on steep slopes and avoid damaging soil, but the actual implementation and understanding of their limitations are in its infancy (Visser & Stampfer, 2016)

Improvements to allow machines to operate on steeper areas are two-fold: the need for increased stability of the base machine on the slope itself, as well as improving the ergonomics for the operator. The latter has proven to be the easiest to resolve (Schiess et al., 1983). With the goal of rationalising timber harvesting in steep terrain, early developments in North America included tracked machinery equipped with processors, feller buncher or harvester heads. Empirical studies showed reduced productivity and operability when operating the machine without a self-leveling cab (Schiess et al., 1983). Based on such results, many new steep slope purpose-built machines were equipped with a self-leveling cab and boom. The greater the ability to self-level the cab and boom, the steeper the terrain that could be operated on (Peters, 1991). There is a limit concerning the physical feasibility of operating machines on steep slopes (Hunter, 1993). The loss of traction will prevent the machine from moving up and down the slope, but in terms of failure, the real safety concern is the risk of machine roll-over. Most forestry machines have relatively a low Centre of gravity and are technically very stable in their intended direction of drive, both uphill and downhill.

In New Zealand, the revised Approved Code of Practice for Safety and Health in Forest Operations (MBIE, 2012) contained a section for winch-assisted harvesting on steep slopes and references to specific slope limits have been removed. Specifically, it requires all mobile plant using the assistance of a wire rope and/or winch shall be specifically designed, tested, demonstrated to be safe and that the tension on the wire rope shall be restricted to 33 percent of its breaking load at all times.

Forest Product Innovations conducted two trials in 2017 to compare productivity and soil disturbance of a Tigercat 635E skidder (Strimbu & Boswell, 2018). The skidder was assisted by an Ecoforst T-Winch in one trial, and it was unassisted in the other trial. The results showed that productivity is higher with winch-assistance; potential benefits were also found in fuel economy and extended machine life.

Winch-assist harvesting systems are designed to provide health and safety, environmental, and productivity benefits in commercial logging operations on steep slopes up to 50 degrees (Hancock Forest Management, 2016). In recent years a strong industry drive has seen a focus towards more mechanised operations, to achieve greater safety and cost-effectiveness on steep terrain (Visser, et al., 2014). Mechanised harvesting is known to have a significant reduction in stump height. In the average Radiata pine clear-fell block a 10 cm reduction in stump height will recover about 6m^3 /ha of pruned log volume – worth $700/ha (Raymond, 2012).

Raymond (2012) highlights that the aim of tree felling is to aid the subsequent extraction phase. Felling a tree in a direction that the following operations (delimbing and extraction) are helped as much as possible. A pre-requisite of felling is that the work is performed in a safe way.

Commonly raised issues with manual felling are the high physical workload associated with good practice, labour turnover, and shortage of skilled workers. Therefore, manual felling practices that maximise value recoveries such as low stump heights and cross-slope felling are not standard. Mechanised felling is the only practical way to consistently perform cross-slope felling and hence gain a reduction in felling breakage (Raymond, 2012).

One relevant study conducted in Nelson, New Zealand by Malietoa (2016) looks at the system production balance within three different mechanised harvesting case studies. It was found that the three operations differed depending largely on piece size. Not enough data was compiled concerning delays and therefore the production is based on a delay-free environment. It was found in case study one that work elements were often completed in random order due to operator preference and site conditions. The first case study had an average stand piece size of 1.6m^3, delay-free productivity (per PMH) was calculated at 69.6m^3/PMH from 43.5 trees felled/PMH (204 felling cycles overall). Case study two had a similar cycle time. However, the productivity was higher due to a larger piece size of 2.3m^3 translating to an average delay-free hourly productivity of 43.3 trees or 99.5m^3/PMH (220 cycles overall). The third case study observed wind throw 74 times throughout the 252 cycles. Moreover, this case study had the greatest productivity of 109m^3/PMH from 47.4 trees felled/PMH. Productivity was influenced by the piece size of 2.5m^3, considering windthrow is known to have a negative effect on productivity; this would not normally be expected. Overall, this study found the productivity of three winch-assist harvesting systems; 69.6m^3/PMH, 99.5m^3/PMH, and 109m^3/PMH.

Shifting position between stems significantly affected cycle time. However, it would be impractical to shift the machine position between trees if deemed unnecessary. The major factors that could be influenced to assist overall production are increased bunching and shoveling. Bunching was found to reduce productivity by 24.1m^3/PMH and 20.9m^3/PMH for case studies one and two. However, bunching has been shown to increase the productivity of extraction for case studies one and two. A key finding in this study was the potential solution to maintain high utilisation rates was to use one WAM across multiple operations. This would, however, raise issues with transport costs and work availability at alternate operations.

A study by Amishev & Dyson (2018) has been conducted with the aim of assessing winch-assisted feller-buncher and grapple yarder productivity. The study was carried out in Northern British Columbia, Canada near Chetwynd by FPInnovations. The stands were a mix of lodgepole pine (Pinus contorta), white spruce (Picea glauca) and a small amount of balsam fir (Abies lasiocarpa). All three sites were winter-harvested, and most of the ground was frozen and covered in various amounts of snow and ice with slopes ranging from 40 to 85 percent. Operators were experienced with feller-bunchers but relatively new to winch-assist operations, which may have contributed to low productivity. It is mentioned that none of the sites would have been harvested with conventional untethered feller-bunchers due to slope and terrain constraints, which were proven too difficult. Overhead hazards from snowfall meant this site was not safe to carry out manual felling.

The average productivity of the feller-bunchers at the three sites measured was 42.8 m^3/PMH. It was clear from site observations that the low productivity in this study was affected by a relatively small piece size of 0.27m^3, 0.36m^3, and 0.23m^3 at sites one to three, respectively. Poor stem quality also had an effect on productivity because of the Mountain Pine Beetle attack. Steep frozen conditions also had an impact on productivity, proving difficult for the machine to move around the slopes.

The observed overall average feller-buncher productivity was 141.8 stems/PMH, which was significantly higher than recorded by (Malietoa, 2016). The larger amount of stems felled may have been due to the type of felling head (hot saw), being able to fell numerous stems in a single cycle due to the smaller piece size and a significantly greater number of stems/ha compared to (Malietoa, 2016). Amishev and Dyson (2018) mentioned that the reported feller-buncher productivities are higher with continuous rotation disc saws (hot saws) compared with feller-director heads.

Based on five months of shift level time, utilisation of the winch-assist buncher was 71 percent, recorded from an FPDat1 data logger installed on the feller-buncher from May to October. Utilisation would have been higher without the half-hour warm-up period for the winch hydraulic fluid during the colder months. The elements of the winch-assist operation requiring the most time were; fell and bunch (50.7%), moving (24.9%), brushing and moving debris (10.1%), moving the WAM (7.6%), delay (4%) and the last 2.7% being made up of other elements.

Acuna, Skinnell, Mitchell, & Evanson (2011) looked at the productivity of a Valmet 445 EXL tracked self-leveling machine with a Valmet 233 fixed felling head. This machine was a conventional feller-buncher operating near Yarram, on the South Gippsland coast of Victoria, Australia. The stand consisted of a mature 33-year old radiate pine plantation of approximately 1,065 trees per hectare with no notable understorey. It is mentioned that there was excellent traction, having dry, sedimentary-based soils, which helped in steep terrain. The average slope was 27 degrees, which is well within the safe operating limits of a feller-buncher.

The observed overall average feller-buncher productivity was 172 stems/PMH. It was stated that the piece size ranged from 0.1 to 1.3 m^3 resulting in productivity of 19.6m^3 to 206.3m^3. However, the mean piece size was 0.8m^3, which gave an average productivity of 138m^3/PMH. This study confirmed that both time required for felling and bunching increased with an increasing diameter at breast height (DBH). Acuna and others (2011) noted that the high stocking level of more than 1000 stems per hectare enabled a high ratio of trees to be felled per move. This was found to be a contributing factor to high productivity.

The three studies identified several indicators that affect the productivity of winch-assist harvesting systems. Piece size was found to be the most common reason for different productivity between the three studies and within each study. It was found that a larger piece size increased productivity although it slows the overall cycle slightly. Higher stocking also increased productivity, as the machine requires less movement (shifts) between each cycle. Factors that were found to have a negative impact on productivity were steeper terrain, which decreased productivity, having an effect on the speed of the machine on the slope. Poor soil quality and frozen ground can slow the machine making each cycle longer. Amishev and Dyson (2018) Found that continuous rotation disc saws (hot saws) are more productive than feller-director heads. A summary of the studies is shown in table 1.

Table 1. Summary of existing studies.

	New Zealand						Canada			Australia
	1		2		3		4	5	6	7
Block Area							54.7	125.6	86.7	>100ha
Volume (m^3/ha)	577	349	545	487	653	420	312	316	292	852
Average stem volume (m^3)	1.23	1.6	2.5	1.47	2.3	1.64	0.27	0.36	0.29	0.8
Stocking (SPH)	469	218	218	331	284	256	1155	877	1006	1065
Average slope (%)	29	26	25	22	13	27	38	56	46	40
Max slope (%)	41	34	34	29	25	35	85			47
Productivity										
Stems/PMH	43.5		43.3		47.4		150.1	122.4	171.6	172
M^3/PMH	69.6		99.5		109		40.5	44.1	49.8	138

3. Overview of Existing NZ Winch-Assist Systems

There are six main winch-assist systems in New Zealand; Performance and Mechanical Engineering (PME) of Taupo, Waka Welding Ltd of Waikouaiti, Otago; Remote Operated Bulldozer (ROB) manufactured by Rosewarne & May Ltd of Whangarei; Tractionline manufactured by Electrical and Machinery Services Ltd (EMS) of Rotorua; Falcon Winch Assist manufactured by DC Equipment Ltd of Brightwater, Nelson and ClimbMax manufactured by Trinder in Nelson. There have also been approximately 12 machines built by independent loggers or engineering workshops.

3.1. Waka Welding Ltd. (WAKA)

The Waka Welding Ltd winch-assist system was established in Waikouaiti, 40 km north of Dunedin. The Waka winch-assist system began with the collaboration of Waka Welding Ltd. and Jesco Hydraulics and Pneumatics. As of March 2019, Waka Welding Ltd. had produced six winch-assist units operating in Southern New Zealand Regions; Southland, Otago and Canterbury (N. Hill, personal communication, March 6, 2019). The six Waka winch-assist units have been attached to base machines provided by the respective contractor. A single contractor in the Canterbury region designed a winch-assist system with the help from Waka Welding Ltd, built in the contractor’s workshop.

Figure 2. Waka Welding Ltd. Winch-assist.

The Waka winch-assist machine is a single drum having constant pull pressure, preventing the rope from sagging and tightening. Constant pressure prevents juddering and provides a smooth incline when moving up slope (N. Hill, personal communication, March 6, 2019). Waka Engineering Ltd. does not have a specification sheet; however, (N. Hill, personal communication, March 6, 2019) indicated that the max pull is 20 tonne and the bands slip at 20 tonne, mitigating any possible stress on the drum.

3.2. Remote Operated Bulldozer (ROB)

The Remote Operated Bulldozer (ROB) is manufactured by Rosewarne Cable Loggers Ltd and forest machinery engineer, Lain May. ROB is located in Northland, New Zealand and is the intellectual property of Rosewarne and May Limited, New Zealand. As of March 2019, 29 ROB units were sold worldwide with 15 operating within New Zealand and 14 operating internationally. The ROBs sold internationally are used in forest operations and oil and gas operations. The ROB is a state of the art forestry machine that uses winch-assisted, dynamic rope systems based around a bulldozer. The ROB is predominant in North America, represented by Island Pacific logging.

The ROB has a twin winch system with each rope having a 21 tonne safe working load with spring loaded fail safe brakes on each winch drum (Rosewarne, 2019). The ROB utilizes a hydrostatic drive allowing greater operator control, including measuring how much rope goes out and how slow or fast it unravels. The ROB is equipped with tension monitors that allow the operator to check the winches are functioning correctly. The ROB has a detection system with instant shut down of the drums in the event of rope jumping off winches. The ROB is also electronically alarmed meaning the machine will automatically shut down if water overheats, the oil runs out, or a hose blows (Rosewarne, 2019).

Figure 3. Remote Operated Bulldozer (ROB) Winch-assist.

Rosewarne (2019) mentions that the main benefit of a bulldozer rather than an excavator is the low centre of gravity, providing increased stability. Bulldozers can also use the blade as an anchor, lowering the chance of movement. Conversely, excavators are equipped with buckets that can also act as an anchor. The fairleads on the ROB WAM allow the SSM to move up to 45 degrees either side of the bulldozer. ROB provides comprehensive staff training to all operators to ensure they can confidently operate the ROB in a safe manner. Warranties are included plus a servicing and maintenance schedule.

3.3. Electrical and Machinery Service (EMS)

The Electrical and Machinery Service (EMS) Tractionline winch-assist is designed, manufactured and tested in Rotorua, New Zealand. EMS was founded by Chris Hancock in 1995 who is currently the managing director. EMS specialises in electric over hydraulic systems such as the Harvestline, Tractionline, Hawkeye and general forestry machine guarding. EMS has produced 96 Tractionline units with 36 of these operating in New Zealand, 45 in North America and 15 in Australia and Chile combined (B. Griffiths, personal communication, March 26, 2019). Tractionline is represented by Technical Forest solutions (TFS) in North America.

Tractionline is a twin winch system running constant tension with large back up and emergency brakes that are controlled via wireless communication between the two machines; WAM and SSM. The designing, manufacturing and testing employs multiple Computer-aided design (CAD) and Computer-aided manufacturing (CAM) and computer-aided stress analysis procedures. The designs use the highest quality proprietary components available. Multiple safety redundancies and a real time operator display interface ensure safe operation of the system (Electrical, 2019).

Figure 4. Electrical and Machinery Service (EMS) Tractionline Winch-assist.

Tractionline recommends a base machine heavier than 25 tonne as their modular winch mounts are designed to replace factory counterweights on excavators greater than 25 tonne. The Tractionline unit is compatible with old machinery, high hour machinery and the innovative control system can be installed in most steep slope machinery.

3.4. Falcon Forestry Equipment (FFE)

The Falcon Winch-assist system is produced in Nelson, New Zealand by DC Equipment. DC Equipment was founded in 2006 as DC Repairs by Dale and Christine Ewers. DC Equipment produces a range of different forest harvesting products such as; Falcon Winch-assist, Falcon Claw, Falcon grapple camera and Falcon skylight. DC Equipment had produced 90 FFE Winch-assist machines as of March 2019 with 45 operating in New Zealand, 25 in Chile, 12 in Canada and 8 in the United States of America (H. Campbell, personal communication, March 27, 2019).

The Falcon Winch-assist system is a single drum unit with a 28mm rope that can be fitted to any excavator over 27 tonnes. The FFE Winch-assist system was developed in the forest with collaboration from logging crews. Feedback from contractors has allowed DC Equipment to create an uncomplicated, simple to operate and easy to maintain system. The FFE winch-assist is designed to be a multi-purpose machine; equipped with a quick hitch that allows digging, loading and shovelling.

Figure 5. Falcon Forestry Equipment (FFE) Winch-assist.

FFE has put a lot of emphasis into safety features that have been developed to eliminate risk while operating the FFE Winch-assist (DC Equipment, 2019). A significant safety feature is the over speed alarm triggering a rope management system in the winch which automatically slows it down to prevent shock-loading. There are many other alarms such as; movement alarm to alert the operator is the winch machine experiences any movement, a cab door tamper detection alarm, over tension alarms, drum over speed alarm/arrest and a maximum rope pay out alarm/arrest. The FFE also has a live feed camera system for the operator monitoring the engine bay and winch drum (DC Equipment, 2019).

3.5. ClimbMax

The ClimbMax steep slope harvester was developed by Trinder, a Nelson-based engineering and electrical firm and Nigel Kelly, a logging contractor. The ClimbMax is commercially available through ClimbMax Equipment Ltd. ClimbMax has sold 11 winch-assist machines worldwide with three operating within New Zealand, seven in Canada and one in the United States of America.

The ClimbMAX steep slope harvester is an excavator equipped with a felling head and a single winch mounted to the excavator base. The ClimbMax can be classed as a rebuilt excavator, with every component except the radiator totally remodified from the ground up, and eight tonnes of weight removed to lower the centre of gravity at the base. One modification is a high tensile steel boom with a longer 10-metre reach attached to the grapple, this addition is to increase reach and aid manoeuvring on the slope. The ClimbMax has a 42 tonne gross weight, including a 2.3 tonne head unit, and 190kW power output. The winch holds a 380m cable with a 15 tonne line pull (Watson, 2016).

Figure 6. ClimbMax International Ltd. Winch-assist (ClimbMAX International Ltd, n.d.).

The ClimbMax is capable of felling trees on slopes up to 45 degrees, bunching stems for yarder extraction or felling and shovelling tress to a ground based extraction point (ClimbMAX International Ltd, n.d.). The main difference from other excavator harvesters is its fully integrated computer driven winch system working in tandem with the WAM.

3.6. Performance and Mechanical Engineering

The Performance and Mechanical Engineering (PME) winch-assist machine was developed in Taupo by Performance Mechanical & Engineering Ltd. PME has produced five winch-assist machines that are operating within New Zealand as of March 2018. The PME is commercially available in New Zealand.

Peacocke logging of Taupo approached PME wanting to engineer a system that would improve productivity when felling on steep slopes. The solution was to develop a dual winch drum system to fit a bulldozer, acting as an anchor for a feller-buncher on steep slopes (Performance Mechanical & Engineering Limited). The PME is controlled remotely via the SSM, meaning no operator is required in the bulldozer.

Figure 7. Performance & Mechanical Engineering (PME) Winch-assist.

The outcome of the PME winch-assist machine is the reduced risk of accidents due to unprotected manual hand fellers no longer being required on dangerous steep slopes (Performance Mechanical & Engineering Limited).

3.7. International Systems

New Zealand is dominated by pine plantations with a rotation age between 25 - 28 years. Forest plantations of these characteristics generally produce a large tree size requiring robust large machinery to fell and handle trees on the slope. The environmental regulations in NZ allow yarding over waterways and large cut block areas, which are suitable for winch-assist cable yarding operations.

Winch-assist was first established in Europe in the late 1980s for forwarder extraction. The winch-assisted forwarders aim was to match the productivity of harvesters on slopes. In the early 2000s as steep slope fibre supply increased, European winch-assist systems expanded to harvesters. There are now more than 800 commercial units in use. European forest management has a large emphasis on mitigating ground disturbance. Furthermore, winch-assist systems are commonly wheeled machines, having less ground disturbance than tracked machines. European forests are partially cut, causing difficulties with roading. Winch-assist can allow less roading, extracting strips of a forest up to a road rather than roading through the slope. European operators are highly trained before operating machinery, ensuring they are competent and able at operating expensive machinery in sensitive land areas.

The common European winch-assist manufacturers are; Haas, Herzog, Komatsu, Ecoforst and Konrad. It is common to see European winch-assist systems bolted to machines working on the slope. This is achievable due to the lightweight machines used in forest operations.

The Timber Max is reported to be a robust, powerful and compact winch unit that allows loggers versatility depending on the harvesting equipment available (Timbermax). The different applications are displayed in Figure 8 below.

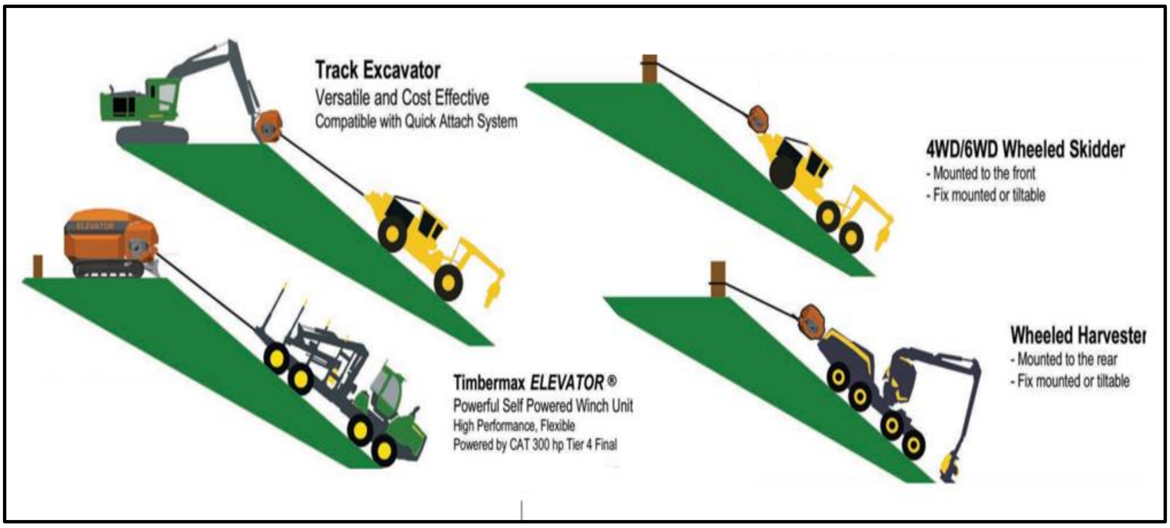

Figure 8. Timbermax applications on steep slope machinery (Timbermax).

North America is currently facing the ‘above the road’ problem, which is commonly due to the lack of infrastructure on top of ridges and the inability to gain access to ridges. This issue creates difficulty for most WA systems, as the WAM is generally required at the top of the slope. FPInnovations developed a backpack winch that enables a person to hike up a slope carrying a straw line used to pull the winch-assist rope up and anchor off a stump. For this application in North America, the NZ manufactured ClimbMax can be used.

The T-Winch is a traction winch system, developed in Austria by Ecoforst. The CEO of Ecoforst is Marcus Krenn, a harvesting contractor in Austria. The T-Winch is a self-propelled traction winch, which has 500m of cable incorporated within it and allows a harvesting machine to be attached to the T-Winch. Tension on the cable is constantly maintained as the computer controls an advanced closed hydraulic system, preventing the cable from sagging or bouncing. The smooth and reactive operation avoids shock loading on the cable and ensures maximum traction on slopes (ecoforst, n.d.).

T-Winch is currently operating with a number of timber harvesting gangs in Central Europe and according to (Parkinson, 2016), six T-Winches were operating in the forestry industry in Chile. This is also supported by (Friday off cuts, 2018) mentioning 80 original T-WINCH 10.1 machines have been sold all over the world through dealers based across Europe, North America, South America and now New Zealand and Australia. The latest T-winch development are the 20.2 and X.2 machines (Figure 9).

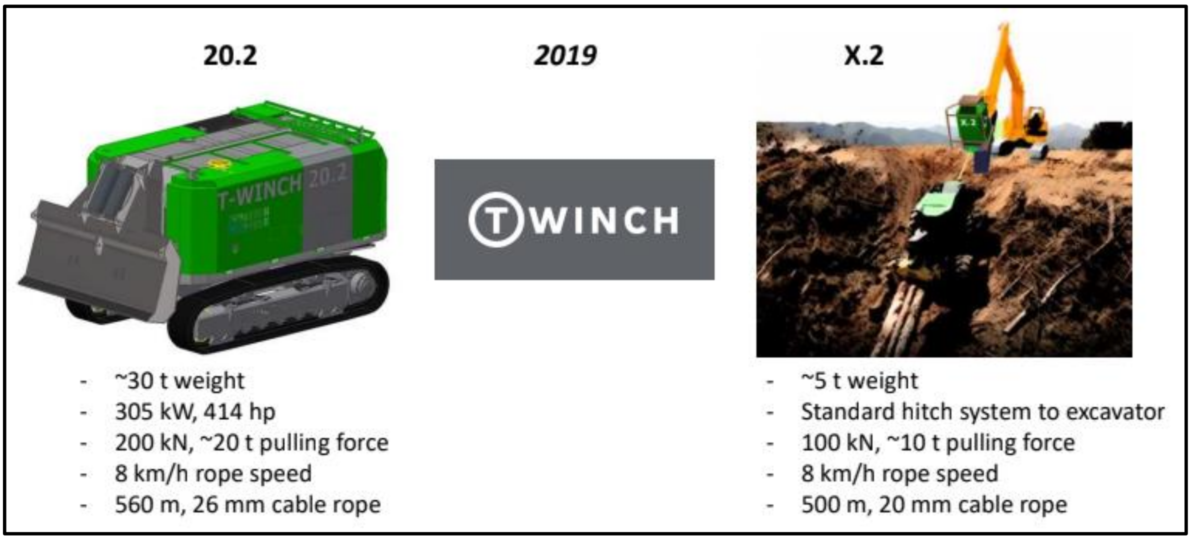

Figure 9. T-Winch 20.2 and X.2 latest developments.

The purpose of the two machines above is working together with the A.2 ground carriage to extract timber with ground-based extraction methods using an A.2 ground carriage with a clam bunk grapple. To achieve this, the 20.2 secures the SSM to the slope, the A.2 moves up and down the wire rope however, the rope only serves as a guide. Moreover, A.2 is secured by the second X.2 wire rope and is controlled by an operator at the top of the slope that unloads and returns to the SSM. The SSM loads the A.2 and returns it back up the slope automatically (Figure 10).

Figure 10. T-Winch 20.2, X.2 and A.2 ground carriage working together.

4. Objective

Improve our understanding of winch assist harvesting operations by completing a series of six case studies to establish factors affecting productivity, including different stand (i.e. tree size, stocking) and site (i.e. slope, soil) factors at each site.

Research questions

- What is the productivity and utilisation of six different winch-assist harvesting operations?
- What are the stand and site factors that influence productivity and utilisation?
- What are the reasons for maintenance and breakdowns?

5. Materials and Methods

A comprehensive study has been carried out at six locations, identifying: site and stand details at each site, details of the winch-assist harvesting system as well as elemental time studies.

5.1. Stand and site details

The method of scaling log volumes was determined on site depending on logistics. Where possible butt diameters of trees were measured when safe or directly after hours during shutdowns. Alternatively, stems to be cut were cruised at a safe distance for the felling operation. The stand details were retrieved from the forest managers where possible and if not; diameter to volume relationship was determined by measuring 20 full tree heights/DBH and by using standard volume tables. This information is displayed in Table 1.

All six studies saw different operational techniques and to complete the study safely, efficiently and accurately, assessment techniques had to differ between sites. However analytical techniques were consistent across the study.

The variables measured were reported against the productivity of the corresponding winch-assist operation. Soil was classed from 1 to 3, where 1 is very good soil suitability and 3 is very bad (refer to table 2). Site difficulty was determined by the members of the logging crew and by comparing site observations after completing field work.

Table 2. Soil classification.

Soil Class	Characteristic	Description
1	Good	Stable dry ground, often gravel or sand with good traction.
2	Medium	Stable ground with patches of large rocks or soft ground.
3	bad	Very rocky, muddy or soft often slowing or stopping the operation.

Table 3. Site difficulty classification.

Site Class	Characteristic	Description
1	Easy	Long even slopes with no sharp gullies.
2	Medium	Medium length slopes, although broken in places.
3	Difficult	Short slopes, very broken contour, streams or native bush exist through the site.

5.2. Time study data collection

The objective of production studies is to quantify average cycle times and measured conditions. The sources of variation associated with randomly measured variables, unmeasured conditions, and delays are undesirable (Olsen, Hossain, & Miller, 1998). The results of this research project are dependent on the accuracy of the time study being undertaken, and therefore, the most suitable method to sustain accuracy is the detailed time study. The most common methods for collecting productivity data are detailed time and motion studies and shift-level studies (Olsen, Hassain, & Miller, 1998). The aim of time studies is to analyse time inputs to relate them to operational variables or work conditions, with a typical purpose to analyse operational efficiency (Musat et al., 2015). In general, the detailed time study is more discriminating than the shift-level study. It can detect a smaller difference between means for alternatives than a shift-level study can detect (Olsen, Hossain, & Miller, 1998). The practical uses that can be applied from time study measurements are setting work rates, scheduling harvesting activities, and comparing technologies or work methods (European Cooperation in Science and Technology, 2012).

Because winch-assist systems undertake a variety of tasks, elemental level measurement was used as it consists of splitting the work cycle into practical steps (elements) and then recording time consumption separately for each of them. This allowed the work process to be described in more detail, contributing to a better understanding of process dynamics. The benefits of elemental measurement are: 1) indicating which specific process steps take more time so that specific improvement measures will primarily target these steps; 2) separating effective work time from delay time, since these two categories have different internal variability and could be modelled in different ways; 3) separating functional elements that react to different work characteristics, so that more accurate sub-models can be developed (European Cooperation in Science and Technology, 2012).

The elements recorded are as follows; felling, moving, shovelling and delay. Delay was broken down into three categories; Operational, Mechanical and Personal. The field measurement sheets used in time studies one, two and three are in appendix 2.

The data collection method used in Canada for time studies four, five and six changed due to working with a more extensive research company with existing methods in use. The new data collection method replaced field sheets with an allegro handheld computer; serving as a multi-purpose portable computer in the most demanding outdoor and industrial environments. Allegro handheld computers have numerous benefits; durable hardened plastic in a shear-proof and shock-resistant design, strong chemical resistance, compatible with gloves in freezing conditions and easy to grip. The software used on the allegro computer was TS1000X, allowing preparation of codes and elements before entering the field. TS1000X is compatible with excel workbook allowing fast translation.

Table 4. Time study intervals.

Felling cycle element	Description
Working Felling:	Number of trees: (1,2,3,4,5) Felling head (attached to tree) cuts and fells tree to the ground: Starts when: felling head touches tree. Finishes when: Tree fells and hits the ground.
Bunching:	Felled stems are slewed and repositioned into bunches away from the stand: Starts when: Tree fells and hits the ground. Finishes when: tree is positioned for extraction/not touching felling head/ Begins new cycle.
Brushing:	Any interruption to remove unmerchantable trees and vegetation or clear processing debris.
Moving (travel/shift)	SSM tracks move changing position and attaching to next standing tree: Starts when: Tree is on the ground and stops touching felling head. Finishes when: Tracks have moved and felling head touches next tree.
Shovel (Occurs in replacement to bunching)	Stem is shovelled away from the felled location: Starts when: Tree fells and hits the ground. Finishes when: tree is positioned for extraction/not touching felling head/ Begins new cycle.
Delay	Any interruption to the previous time elements. The cause of the delay (e.g. operational, mechanical or personal) is recorded.

Delays

Delays contribute to a significant proportion of the working day and can have significant impacts on production. Some of these delays are necessary and part of operations, some however are not and can result in systems being far less efficient than they should be. To understand the system, it is important to separate these delays into categories. As such, delay was divided into four categories; 1) operational, 2) mechanical 3) Personal (non-productive) delay and 4) environmental delay (Huyler & LeDoux, 1997). Descriptions of various delays are in Table 7 below. As well as determining the type of delay, the cause and estimated duration was noted (European Cooperation in Science and Technology, 2012).

Maintenance and Breakdowns

Maintenance and breakdowns were recorded as they occurred, maintaining good communication with the machine operators as to what was occurring and why. If interviews were found necessary, a short interview would be conducted on each WAM and SSM operator. Normally there will be one operator per operation, however if there were two, they would both be interviewed. The scope of the interviews was based on a general overview of the operation focusing on reasons for down time and loss of productivity. The interview also gauged the operators' competency and skill based on the judgement of the interviewer.

Table 5. Description of delays.

Delay	Detailed description
Operational	Delays required for the operation to occur, sometimes productive Example; shifting WAM, repositioning on the slope, radio communication or planning.
Relocate WAM	Delays required for the operation to occur, Example; shifting WAM, repositioning on the slope, radio communication, or planning.
Move setting	Moving the WAM and SSM to a new setting within the same forest or cut block (common in Canada with small cut blocks).
Setup/Planning	Planning harvest area each day, walking through forest area confirming the safest and fastest route, tailgate meeting with harvest crew
Assist other operations	Stopping winch-assist operations to assist with other duties within the crew; helping new operators, operating another machine to put in a track.
Diesel	Refuelling either the WAM, SSM or both, requiring walking the machines up to 1km depending on where the diesel is located
Radio	Radio communications within the crew requiring operations to stop as hands are needed to control the radio device.
Line handling	Moving winch line to prevent it from getting caught up when moving across the slope or when working on challenging terrain; often over stumps or cutover. When two ropes are being utilised, untangling and straightening them up is required.
Warm up	The time required for the WAM and SSM to warm up, this often overlapped with setup/planning as they can be carried out at the same time.
Clearing WAM area	Moving debris or earth creating an even safe space for the WAM to be located.
Mechanical	Delay caused by the failure of a piece of equipment, Example; replacing a fatigued hydraulic hose or a bent felling bar
Chain	Chain issues such as chain breaking, chain flicking off the bar, sharpening the chain, replacing the chain
Greasing	Greasing the WAM and SSM, commonly at the end of each day. The SSM requires more intensive greasing being used more. The felling head also requires greasing.
Maintenance	This included functional checks, servicing, repairing or replacing of necessary devices, equipment.
Felling head	Hydraulic hoses, replacing the felling bar
Personal	Delay caused by the operator, Example; toilet breaks, eating, communication with the research team.
Environmental	Delays caused by weather conditions

Safety and environmental practices

Safety and environmental rules and practices undertaken by the six different logging crews and the corresponding forest managers were observed and compared between the different winch-assist operations. The safety practices will be related to safe working areas, slope restrictions, distance between machines, personal protective equipment and scheduled machine hours. The environmental practices were related to soil erosion, water management, slash and recoverable volume.

Challenges

Throughout this research project there were a number of challenges, specifically in regard to field measurement. Being outside, natural factors such as weather may cause disruption. However, as sufficient preparation was undertaken, the severity of this was mitigated. When carrying out the time study, visibility of the SSM was crucial for ensuring correct data points were recorded. The terrain the SSM operates on can be steep and have bluffs making this difficult at times. To guarantee accurate vision, a plan of attack was created with the operator before each day as to where harvesting was to occur and where the best location to observe was. When the SSM was not visible, measurement stopped and the operation was classed as ‘out of sight’.

5.3. Site Locations and Descriptions

Six studies have been undertaken at six different sites between August 20th 2018 and May 5th 2019. Studies one, two and three were carried out in New Zealand in the following regions; Canterbury, Otago and Northland respectively. Studies four, five and six were carried out in British Columbia, Canada in the following regional districts; Clearwater, Carmi and Armstrong respectively.

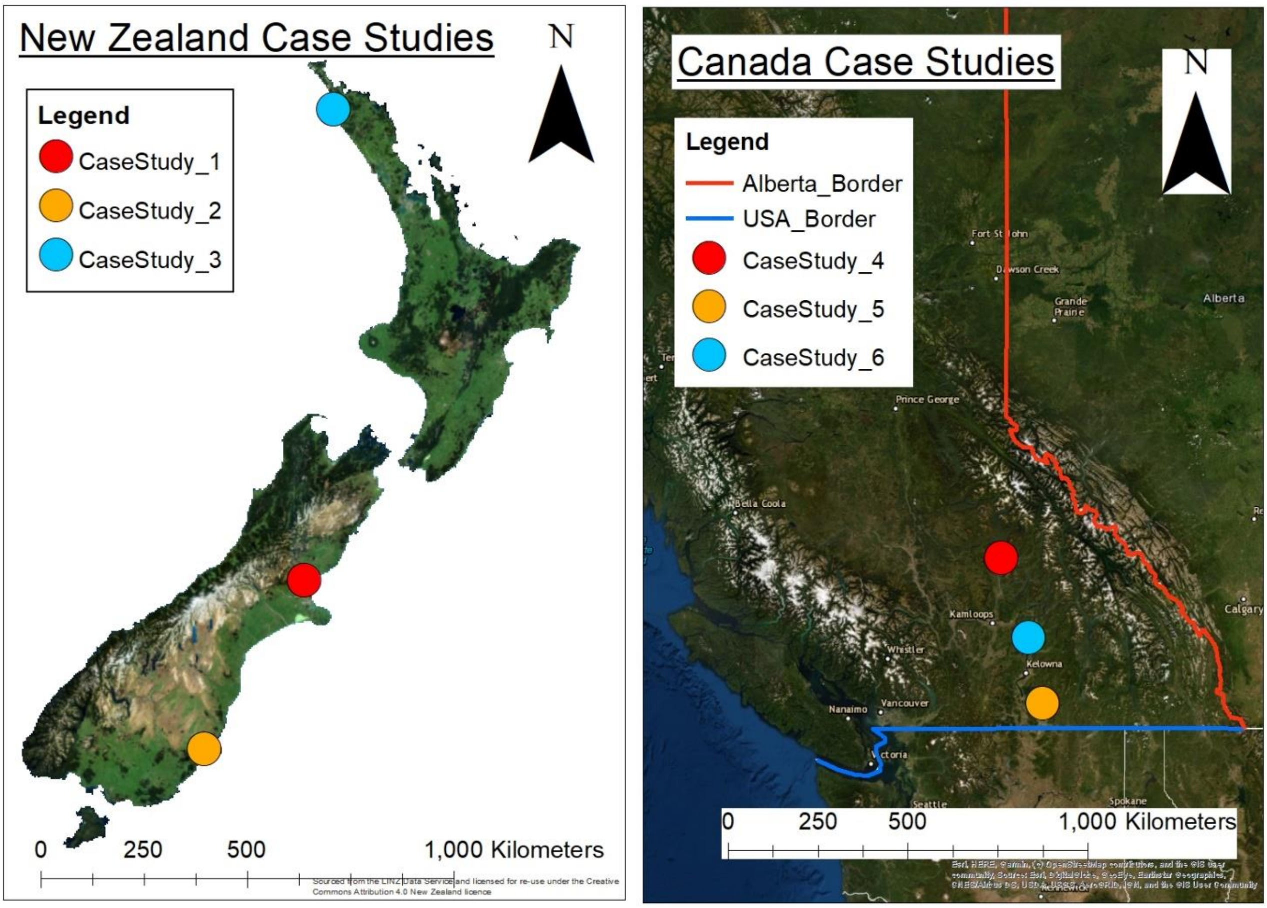

Figure 11. Location of six Case Studies carried out in New Zealand and Canada.

The six case studies were unique with differing stand and site conditions and each contractor having their own combination of WAM and SSM. Stand and site characteristics are shown below in Table 8.

Table 6. Stand and site characteristics of the six case studies.

	New Zealand			**Canada**				
Case Study	**One**	**Two**	**Three**	**Four**	**Five**			**Six**
Site Details								
Crew	Buttons	Gamble	Mold	Wadlegger	Lime Creek			Gorge Creek
Management	Rayonier	City Forests	Summit Forests	Canfor	Interfor			Tolko
WAM	Waka Engineerin g	R.O.B	R.OB	EMS Traction line	FFE			R.O.B
Region	North Canterbury	Otago	Northland	Clearwater , B.C	Carmi, B.C			Armstrong, B.C
WAM	Hitachi Zaxis	John Deere 850J	John Deere 850J	CAT 330D L	Volvo FC3329C			John Deere 850J
SSM	Tigercat LS855D	John Deere 909MH	Tigercat LS855C	Tigercat L870C	Tigercat LX870D			Cat 552
Felling head	Tigercat 5195 directional felling Saw	Woodsman Pro FH1350 Directional felling Saw	Tigercat Directional felling head	Tigercat 5702 continuous rotation bunching saw	Tigercat 5702-26 continuous rotation bunching saw			Satco feller director
Forest	Okuku	Ferny Hill	Herekino	Block D219	10L -88	10L -79	10L-78	Block 183
Block Area (ha)	5.8	19	25.2	12.3	5.1	16.5	23.7	36.3
Volume (m^3/ha)	662	621.1	608	296	290	274	353	361
Average stem volume (m^3)	0.9	2.2	1.9	0.7	0.5	0.74	0.79	0.41
Stocking (SPH)	757	279	320	423	575	368	450	890
Average slope (%)	55	48	53	55	73	67	65	45
Species composition (volume %)								
Radiata Pine		100	100					
Lodge pole pine				4	17	8	1	
Douglas fir	100			4	38	60	27	26
Balsam fir				14	11		4	27
White spruce				78			22	11
Engelman Spruce					26			
Hybrid Spruce								
Western Larch					9	32	38	2
Western red cedar							7	14
Western hemlock								19

Case Study One

The study site was located in Okuku forest near Rangiora in North Canterbury, New Zealand. The study took place over the period of one week from the 6th – 10th August 2018. The harvesting contractor was Button Logging Ltd, a local contractor in the region having two crews contracting to the well-established forest management company, Rayonier Matariki Forests. The WAM operating was one of six WAMs constructed by Waka Welding Ltd of Waikouaiti, Otago. The SSM was a Tigercat LS855D tracked SSM with a Tigercat 5195 directional felling saw (Figure 12).

Figure 12. Waka Welding Ltd WAM and Tigercat LS855D SSM: Case Study One.

The harvest setting was 5.8 hectares of Douglas-fir *(Pseudotsuga menziesii)* with a stocking of 757 stems per hectare. The high stocking and relatively exposed site resulted in a relatively small piece size of 0.88m^3. The average slope throughout the setting was 28.7 degrees although in places where the study was carried out, slopes of up to 35 degrees were recorded with an inclinometer.

The forest site was predominantly rocky and in some cases, rocks and boulders required time to ‘brush’ out of the way when felling and manoeuvring between trees. Table 1 displays the characteristics of the study site and crew.

Table 7. Stand and crew characteristics.

WAM	Waka WAM on tracked excavator base
SSM	Tigercat LS855D
Felling head	Tigercat 5195 directional felling saw
Region	North Canterbury
Forest	Okuku
Harvest setting (ha)	5.8
Volume (m^3/ha)	662
Average stem volume (m^3)	0.88
Stocking (SPH)	757
Average slope (°)	29
Average slope (%)	50
Species	Douglas-fir

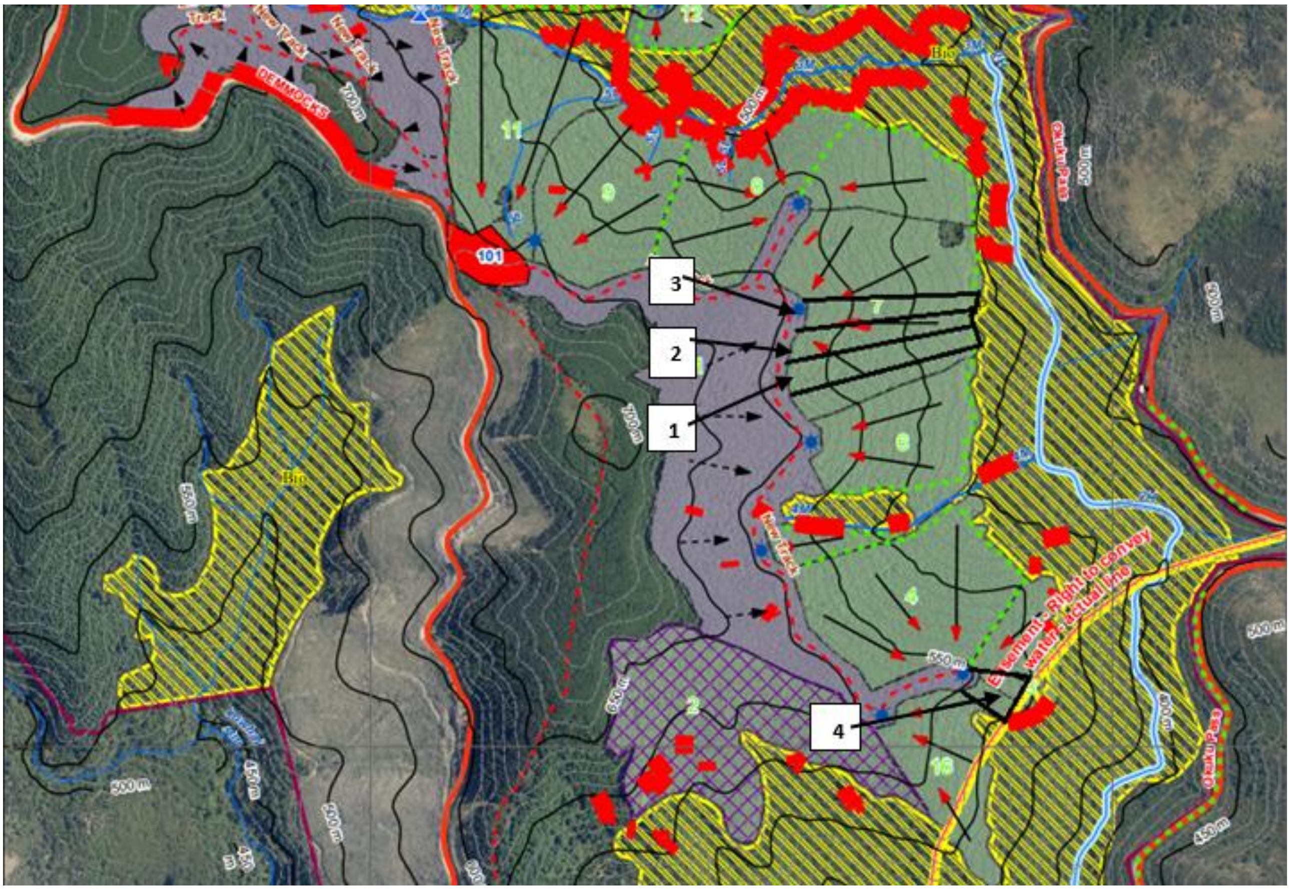

Figure 13. Harvest plan identifying where the winch-assist harvesting system was operating each day.

Winch-assist harvesting was required at case study one to fell and bunch stems on the area of the map shaded green. The dotted red line is a mid-slope track used for extraction and positioning the WAM. The arrows with red pointers indicate the direction the stems were extracted via a swing yarder. The area shaded purple did not require winch-assist harvesting and was either manual felled or mechanically felled by the SSM. Manual felling took place, opening up skid tracks for extraction. Manual felling also took place above the track when the slope was greater than 30 degrees or when banks above the track prevented SSM access.

Table 8. Average corridor length and average slope each day.

Day of study	1	2	3	4	Average
Average corridor length (metres)	270	255	240	75	210
Slope (%)	44	47	50	60	50

Case Study Two

The case study was located in Ferny Hill forest near Mosgiel in Otago, New Zealand. The study took place over a one week period from 20th – 24th August 2018. The harvesting contractor was Gamble Forest harvesting Ltd, a local to the area, holding a long term family relationship of 30 plus years with City Forests Ltd, the forest management company. The WAM operating was a Remote Operated Bulldozer (ROB) manufactured by Rosewarne & May Ltd in Whangarei, based on a John Deere 850 bulldozer. The SSM was a John Deere 909MH SSM with a Woodsman Pro FH1350 directional felling saw (Figure 14).

Figure 14. ROB WAM and John Deere 909MH SSM: Case Study Two.

The harvest setting was 16.2 hectares of Radiata pine (*Pinus radiata*) with a stocking of 278 stems per hectare. The relatively low stocking and long rotation age of 32 years allowed the trees to grow to a relatively large piece size of 2.23m^3 The average slope was 48% although varied across the site; 22% of the area was less than 32%, 37% was between 32 and 50% and 41.6% was greater than 50%. Using an inclinometer, a typical operating slope measured during the study was 47%. The soil was stable, dry, and favourable for ground-based mechanised felling. However, near streams the soil was often wet and soft. There was not much undergrowth meaning limited brushing was required when felling trees and manoeuvring between trees.

Table 9. Stand and crew characteristics.

WAM	Remote Operated Bulldozer (ROB)
SSM	John Deere 909MH
Felling head	Woodsman Pro FH1350 directional felling saw
Region	Otago
Forest	Ferny Hill
Harvest setting (ha)	16.2
Volume (m^3/ha)	621
Average stem volume (m^3)	2.23
Stocking (SPH)	278
Average slope (°)	19
Average slope (%)	33
Species	Radiata pine

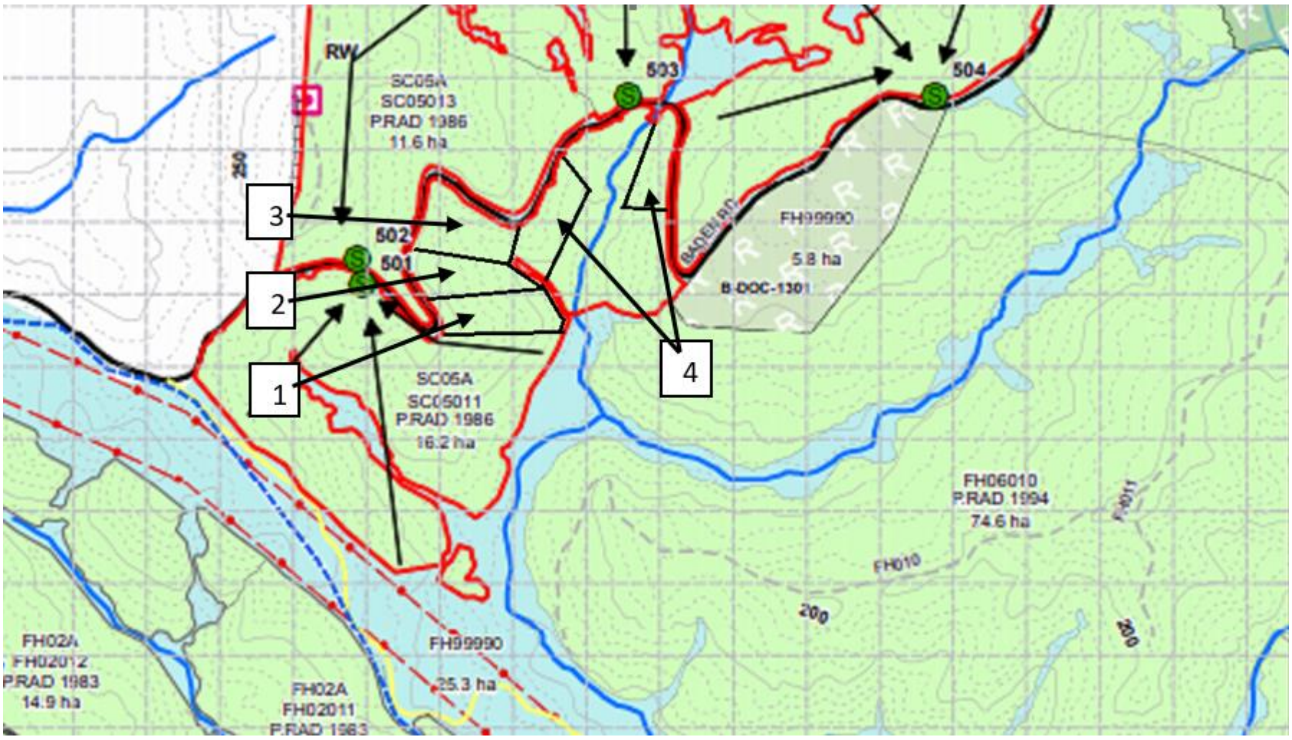

Figure 15. Harvest plan identifying where the winch-assist harvesting system was operating each day.

The long even slopes observed at case study two allowed the WAM to be relocated fewer times than usual. Fewer shifts occurred because the lead angle of the wire rope can cover a larger area when the terrain is round; an example of this can be seen on the map in the bottom left landing. The stems were felled and bunched and extracted via a swing yarder.

Table 10. Average corridor length and average slope each day.

Day of study	1	2	3	4	Average
Average corridor length (metres)	166	166	148	55	134
Slope (%)	45	40	30	60	44

Case Study Three

The case study was located in Herekino forest near Kaitaia in Northland, New Zealand. The study took place over a week from the 29th of April until the 23rd of May, 2019. The harvesting contractor was Mold Logging Ltd and the forest management company was Summit Forests New Zealand Ltd. The WAM operating was a Remote Operated Bulldozer (ROB) manufactured by Rosewarne & May Ltd in Whangarei, based on a John Deere 850J bulldozer. The SSM was a Tigercat LS855C with a Tigercat directional felling head (Figure 16).

Figure 16. ROB WAM and Tigercat LS855C SSM: Case Study Three.

The harvest setting was 25.2 hectares of Radiata pine (*Pinus radiata*) with a stocking of 320 stems per hectare. The relatively low stocking had allowed the trees to grow to a relatively large piece size of 1.9m$^{3.}$ The average slope was 28 degrees, although it varied across the site. Slopes up to 46 degrees were measured on site with an inclinometer. The soil was clay and shallow in places with a rocky underfloor and was not favourable for winch-assist operations, causing SSM traction issues on steeper slopes. The undergrowth was abundant at an average recorded height of five metres.

Table 11. *Stand and crew characteristics.*

Crew	Mold Logging Ltd.
WAM	Remote Operated Bulldozer (ROB)
SSM	Tigercat LS855C
Felling head	Tigercat Directional felling head
Region	Northland
Forest	Herekino
Harvest setting (ha)	25.2
Volume (m^3/ha)	608
Average stem volume (m^3)	1.9
Stocking (SPH)	320
Average slope (°)	28
Average slope (%)	53
Species	*Pinus radiata*

Figure 17. Harvest plan identifying where the winch-assist harvesting system was operating each day.

Case study three involved winch-assist felling and shovelling the entire setting and forest. Small side cuts and tracks were cut into the slope to allow the SSM on the slope to aid the extraction. The area in red was felled and extracted up to the landing in strips. The operator preferred to work in the gullies rather than ridges.

Table 12. Average corridor length and average slope each day.

Day of study	1	2	3	4	Average
Average corridor length (metres)	201	171	157	155	171
Slope (%)	75	82	84	81	81

Case Study Four

The case study was located two hours North of Kamloops near Clearwater, British Columbia. The study located at 1210 - 1630 m of elevation took place over three days between the 8th of November and the 13th of November 2018. The harvesting contractor Wadlegger Logging & Construction Ltd is currently harvesting under contract for Canfor. The WAM was an EMS Traction Line mounted to a CAT 330D L. The SSM was a Tigercat L870C with a Tigercat 5702 continuous rotation bunching saw (Figure 18).

Figure 18. EMS Tractionline WAM and Tigercat L870C SSM: Case Study Four.

The harvest setting was 12.3 hectares with a stocking of 423 stems/ha; 78% Spruce (Picea engelmannii), 14% Balsam (Abies balsama), 4% Douglas-fir (Pseudotsuga menziesii) and 4% Lodgepole pine (Pinus contorta).

Large rocky outcrops were common in the forest and required blasting for road access. During the study, the soil was frozen and firm. Dense undergrowth required brushing of small stems to gain access to the larger diameter commercial trees. The bunching saw is efficient at brushing, being able to grab multiple trees in a single cycle.

Table 13. Stand and crew characteristics.

WAM	EMS Tractionline
SSM	Tigercat L870C
Felling head	Tigercat 5702 bunching saw
Region	Clearwater, B.C, Canada
Forest	Block D219
Harvest setting (ha)	12.3
Volume (m^3/ha)	296
Average stem volume (m^3)	0.7
Stocking (SPH)	423
Average slope (°)	29
Average slope (%)	51
Species	Spruce, Balsam, Douglas-fir, Lodgepole

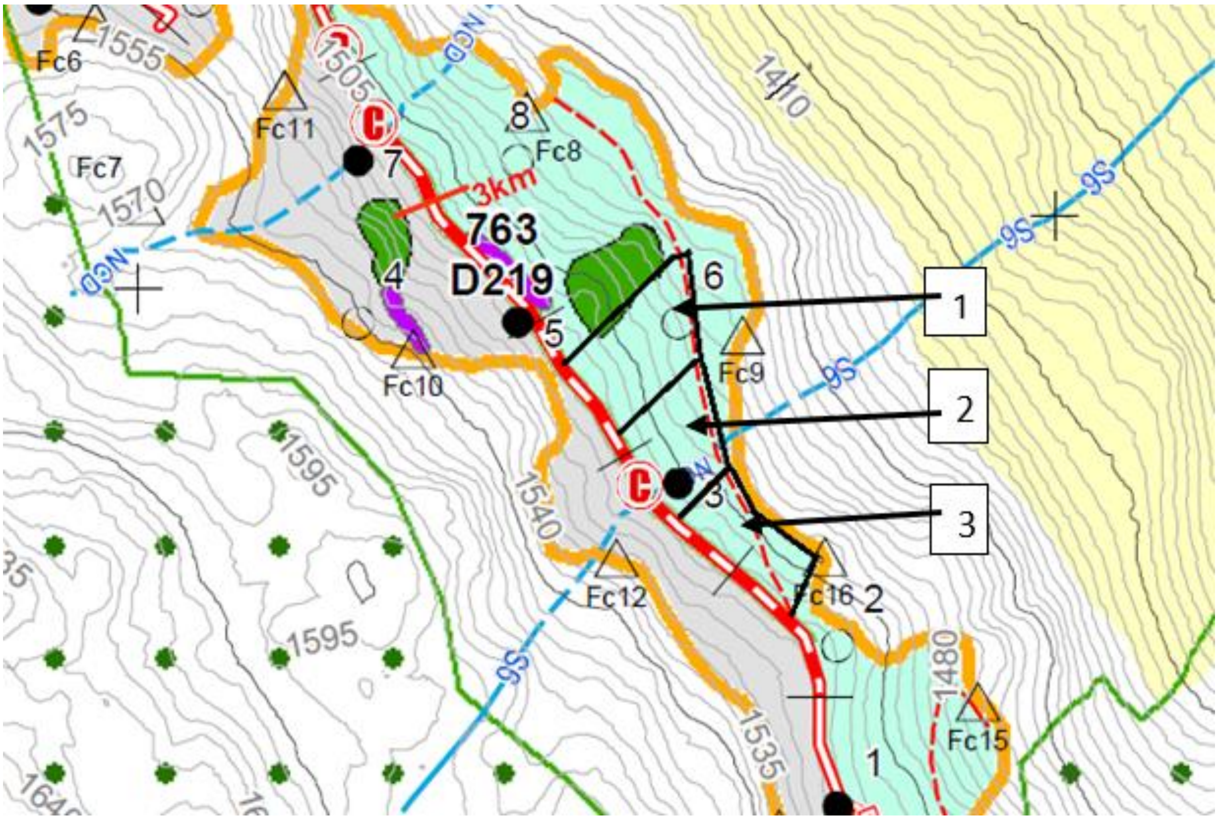

Figure 19. Harvest plan identifying where the winch-assist harvesting system was operating each day.

The area shaded light blue on the above harvest plan was where winch-assist was adopted at case study four. Winch-assist felling and shovelling took place followed by skidder extraction. Shovelling was carried out by a grapple SSM rather than the felling SSM after felling was complete. The permitted harvest area was a 12.3 ha cut block within a large forest. The cut block was narrow and on the side of a slope requiring a mid-slope track for the WAM. The three red dotted lines within the shaded blue are the skidder extraction tracks.

Table 14. Average corridor length and average slope each day.

Day of study	1	2	3	Average
Average corridor length (metres)	75	51	37	54
Slope (%)	45	39	35	40

Case Study Five

The case study was located one hour South-east of Kelowna near Carmi, British Columbia. The study took place over a week from the 26th of November until the 30th of November 2018. The harvesting contractor was Lime Creek Logging Ltd. currently harvesting under contract for Interfor. The WAM was a Falcon Forestry Equipment (FFE) winch mounted to a Volvo FC3329C. The SSM was a Tigercat LX870D with a Tigercat 5702-26 continuous rotation bunching hot-saw (Figure 20).

Figure 20. FFE WAM and Tigercat LX870D SSM: Case Study Five.

Harvesting took place in three settings within the same forest. Setting one was 5.1 hectares with a stocking of 575 stems/ha, Setting two was 16.5 ha with a stocking of 368 stems/ha and Setting three was 23.7 hectares with a stocking of 450 stems/ha. The species within the three settings were; Engelman spruce (Picea engelmannii), Balsam (Abies balsamea), Douglas-fir (Pseudotsuga menziesii), Lodgepole pine (Pinus contorta) and Western Larch (Larix occidentalis).

Rock was observed at the three sites but not enough to impede operations. The terrain was broken within the areas viewed during the study (along with landscape in general). The broken terrain required a mix of conventional untethered felling and winch-assist felling. In areas of the forest, regeneration was thick, specifically in areas where tracks and landings were located during the first growth harvest. Throughout the stand, dense undergrowth required brushing of small stems to gain access to the larger diameter commercial trees.

Table 15. Stand and crew characteristics.

WAM	FFE Falcon on Volvo FC3329C		
SSM	Tigercat LX870D		
Felling head	Tigercat 5702-26 bunching saw		
Region	Carmi, B.C, Canada		
Forest	Block 10L-88, 10L-79 and 10L-78		
Details	Setting 1 (Day 1)	Setting 2 (Day 2 and 3)	Setting 3 (Day 4)
Harvest setting (ha)	5.1	16.5	23.7
Volume (m^3/ha)	290	274	353
Average stem volume (m^3)	0.50	0.74	0.79
Stocking (SPH)	575	368	450
Average slope (°)	36	33	32
Average slope (%)	73	67	65
Species	Spruce, Balsam, Douglas-fir, Lodgepole pine, Larch, Cedar		

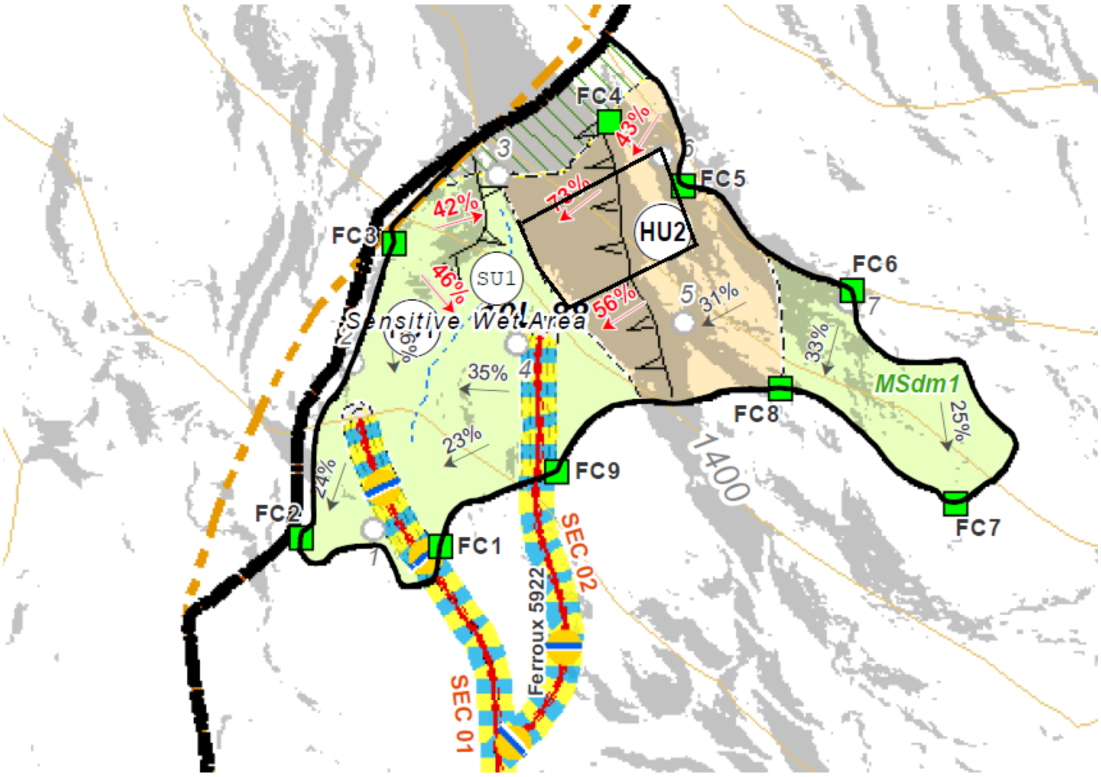

Figure 21. Harvest plan identifying where the winch-assist harvesting system was operating (day one).

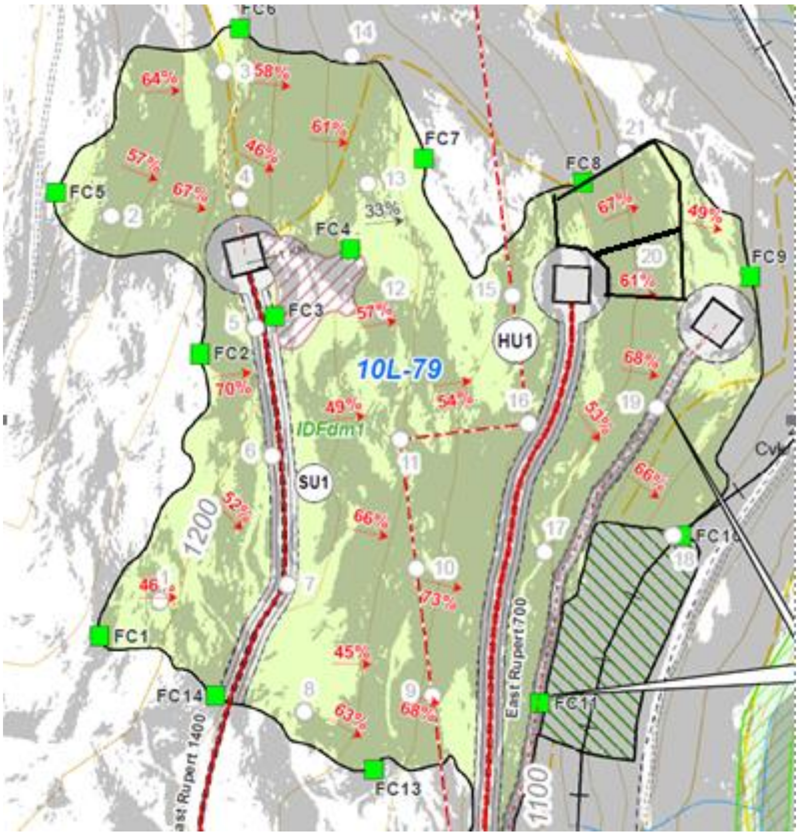

Figure 22. Harvest plan identifying where the winch-assist harvesting system was operating (day two and three).

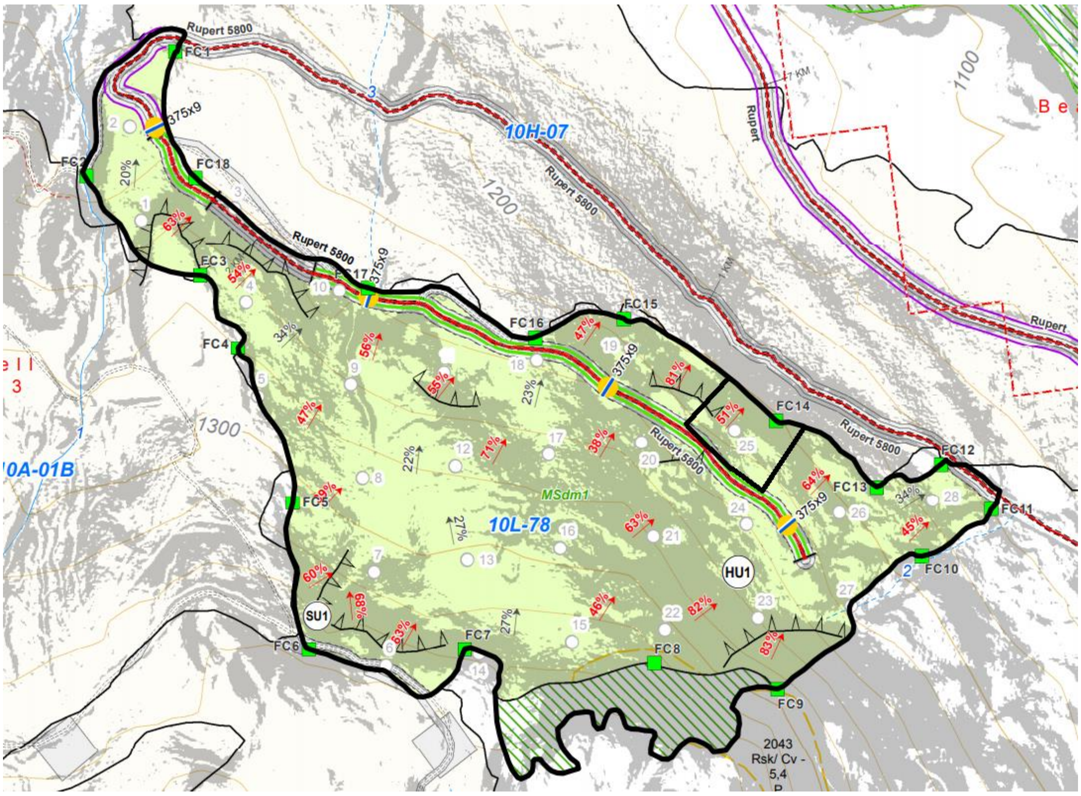

Figure 23. Harvest plan identifying where the winch-assist harvesting system was operating (day four).

Winch-assist has been adapted into this harvesting crew to access areas that conventional machines cannot. The amount of winch-assist felling and shovelling is not significant in comparison to the cut block sizes this logging crew harvests (5-10 ha). Having a small amount of area meant moving sites more frequently. The areas outlined in black in figure 22, 22 and 23 is where winch-assist felling occurred.

Table 16. Average corridor length and average slope each day.

Day of study	1	2	3	4	Average
Average corridor length (metres)	92	100	80	65	86
Slope (%)	64	67	61	51	60

Case Study Six

The case study was located in the Thompson Okanagan Region near Armstrong, a small town one hour North of Vernon, British Columbia. The study took place over two days from the 19th of December until the 20th of December 2018. The harvesting contractor was Gorge Creek Logging Ltd. currently harvesting under contract for Tolko Industries Ltd. The WAM was a Remote Operated Bulldozer (ROB) winch, with a Cat 850J as a base machine. The SSM was a levelling Cat 552 with a Satco feller director head and heel (Figure 24).

Figure 24. ROB WAM and Cat 552 SSM: Case Study Six.

The forest Setting was 36.3 hectares with a stocking of 890/SPH. The forest was second growth and the piece size was 0.41m^3. Table 1 below displays the stand characteristics provided by Tolko.

Rocks were not frequent and soil did not impede productivity although snow was present at a depth of 1 – 1.5 m. The terrain was relatively easy-going throughout although very steep pitches occurred in places. Throughout the stand, dense undergrowth required brushing of small stems to gain access to the larger diameter commercial trees. Extraction occurred during the felling phase whereby the operator would shovel stems down the slope while felling.

Table 17. Stand and crew characteristics.

WAM	ROB on Cat 850J
SSM	Self-levelling Cat 552
Felling head	Satco feller director
Region	Armstrong, B.C, Canada
Forest	Block 183
Harvest setting (ha)	36.3
Volume (m^3/ha)	361
Average stem volume (m^3)	0.41
Stocking (SPH)	890
Average slope (°)	24
Average slope (%)	45
Species	Douglas-fir, Western Cedar, Western Hemlock, Balsam, Spruce

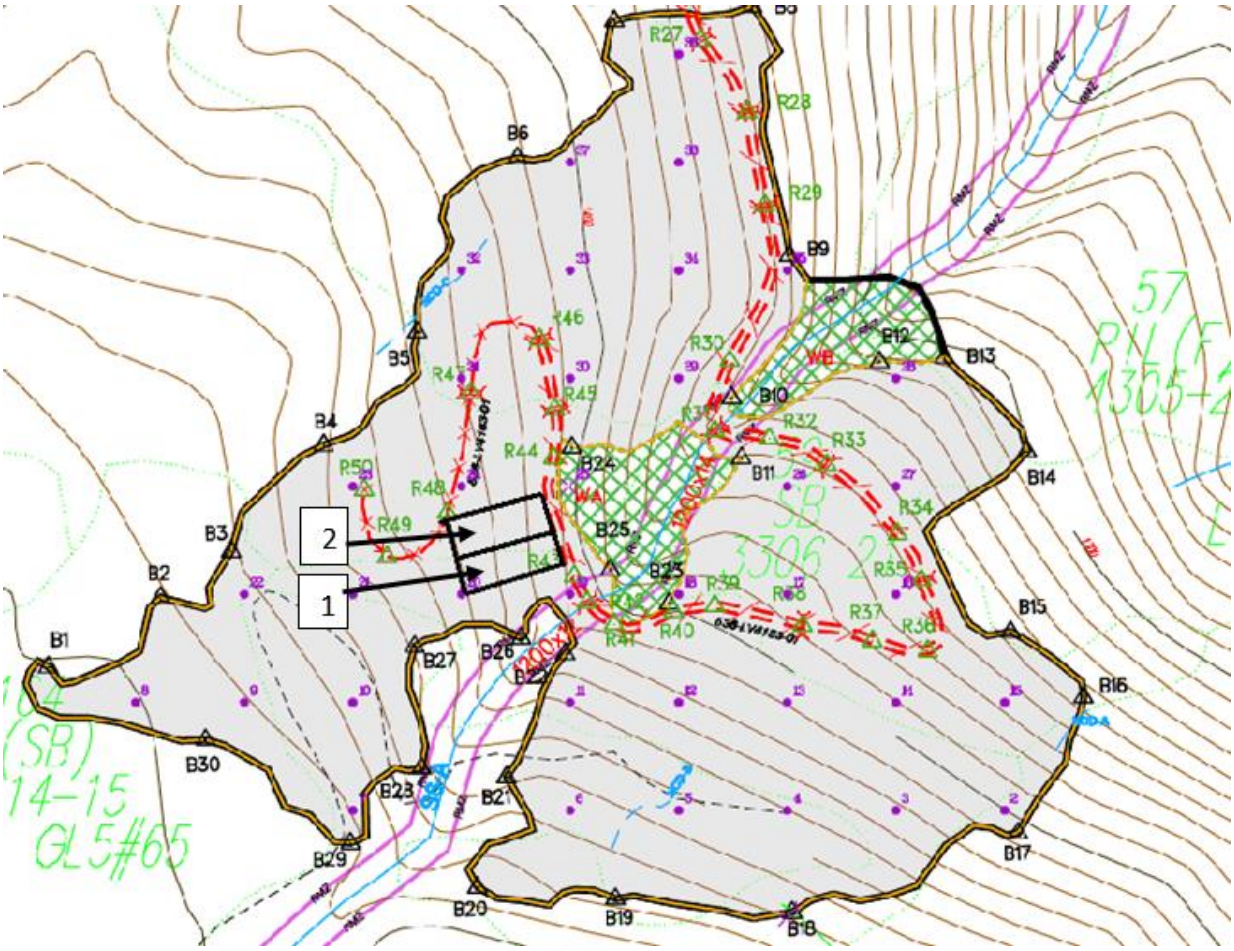

Figure 25. Harvest plan identifying where the winch-assist harvesting system was operating each day.

The harvest plan above displays the harvest area at case study 6. The area-shaded green remains standing as riparian protection and the red line is the forest road. The area shaded purple was harvested using winch-assist. The contractor shovelled stems to the roadside for processing by a second independent crew. Limited access and locations for the WAM to be located meant using standing trees to redirect the wire rope and not moving the WAM.

Table 18. Average corridor length and average slope each day.

Day of study	1	2	Average
Average corridor length (metres)	87	93	90
Slope (%)	28	32	30

6. Results

6.1. Data overview

Table 14 displays the results of the six case studies, identifying utilisation and productivity by productive machine hour (PMH) and scheduled machine hour (SMH). Study time, stems felled and volume is also included.

The average utilisation recorded through six case studies was 52%, ranging from 22 to 63%. The highest utilisation of 63% was observed at case study one while the lowest of 22% was observed at case study three. The main difference in utilisation between case study one and case study three is a result of the SSM core duties. At case study one, felling and bunching for yarder extraction was the priority, with a small amount of shovelling on skid tracks. At case study three, felling and shovel extraction upslope was the priority as the yarder was in the workshop and the terrain was too steep for tracking in with other machines.

Table 19. Results of six winch-assist harvesting Case Studies.

	New Zealand			Canada			Average
Case Study	1	2	3	4	5	6	
Study time (hours)	30.6	27	20	14.2	17.6	13.3	122.7
Stems felled	1296	707	117	755	823	638	4336
Volume (m^3)	1140	1,576	222	529	593	262	4322
Utilisation (%)	60	57	25	63	51	57	52
Productivity (m^3/PMH)	62	102	42	60	66	34	61
Productivity (m^3/SMH)	37	58	11	37	34	20	33

The average productivity per PMH through six case studies was 58m^3/PMH. The site with the highest productivity of 88m^3/PMH was case study two while the lowest was case study six at 34m^3/PMH. Case study two was favourable for high productivity with long slopes and a large piece size requiring little bunching. Several factors led to the low productivity at case study six; small piece size, high stocking, deep snow, bunching and shovelling.

The average productivity per SMH through six case studies was 29m^3/SMH. The lowest productivity of 11m^3/SMH was observed at case study three influenced by the low utilisation as shovelling took place on steep slopes 47% of the study. The highest productivity per SMH was observed at case study two, following the trend of PMH productivity.

The study time through the six case studies was 133.3 hours, observing 4053 stems felled equating to a volume of 4024m^3 with each case studies respective piece sizes. The overall productivity, in this case is 30.2m^3 /SMH.

The proportion of time observed through six case studies broken down into working, moving, shovelling and delay (Figure 26). Delay was found to have the largest impact on winch-assist harvesting systems at all six case studies. Delay included operations preventing the core duties from being carried out. Delay was broken down into operational, mechanical and personal (Figure 27).

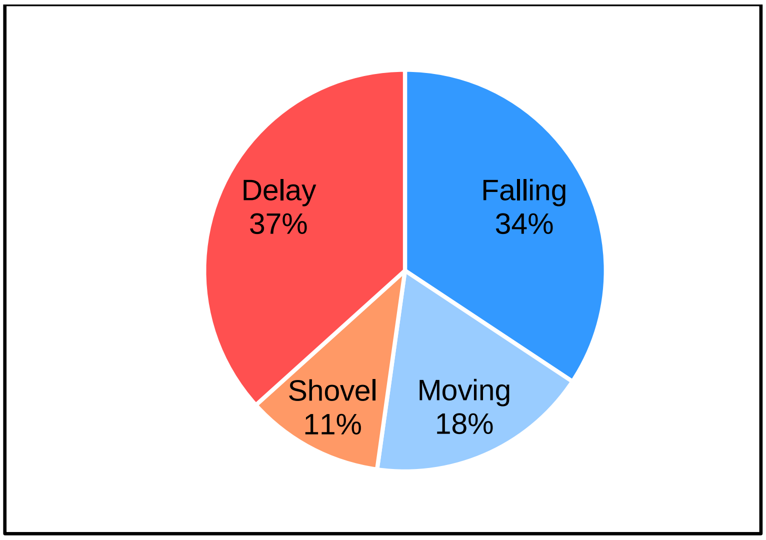

Figure 26. The proportion of operating time recorded through Six Case Studies.

Figure 27 explores the amount of time broken down into the three delay categories recorded at six case studies. The operational delay has accounted for 69% of delays. The most common operational delay was relocating the WAM (29%) followed closely by moving settings (24%) and setup/planning (10%). Chain issues were the most common mechanical delay (8%) while maintenance accounted for 6%. Maintenance included; fixing door handle on a built-in toolbox, replacing hoses and fixing hydraulic leaks, leveller ram issues and a broken wire rope. Personal delay (14%) was a result of unrepresented personal events. A breakdown of all delays is displayed in figure 32.

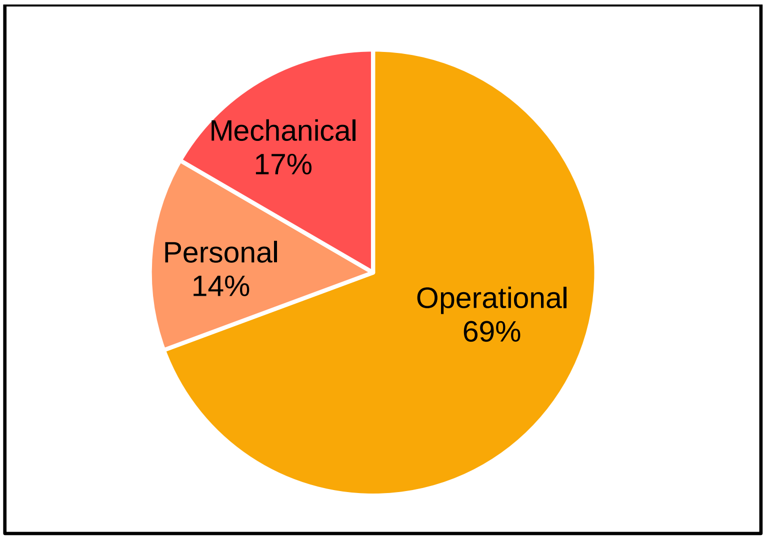

Figure 27. Breakdown of delays into delay categories recorded through Six Case Studies.

The overall working time throughout six case studies varied from 15% to 47% (Figure 28). Working includes time spent felling, bunching and brushing. When the working time was low, it was often a result of extraction, delays and site characteristics such as; low stocking and steep slopes. The studies where percent working time was high were a result of less delays, larger piece size, higher stocking, less shovelling and longer corridor lengths. Longer corridor lengths result in less WAM shifts.

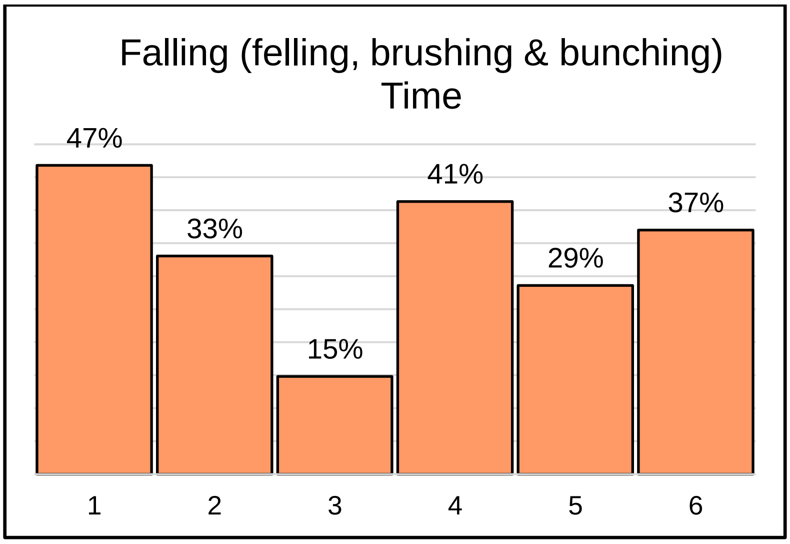

Figure 28. Felling (felling, brushing & bunching) time as a percentage of overall time recorded through six case studies.

The overall percent time moving throughout six case studies varied from 11% to 22% (Figure 29). Moving time is less variable than working time. Moving time was recorded as the time moving on the slope between stems. The time spent moving on slopes when shovelling was not accounted for and furthermore was classed as 'shovelling'. Three of six case studies found 22% of the time was spent moving.

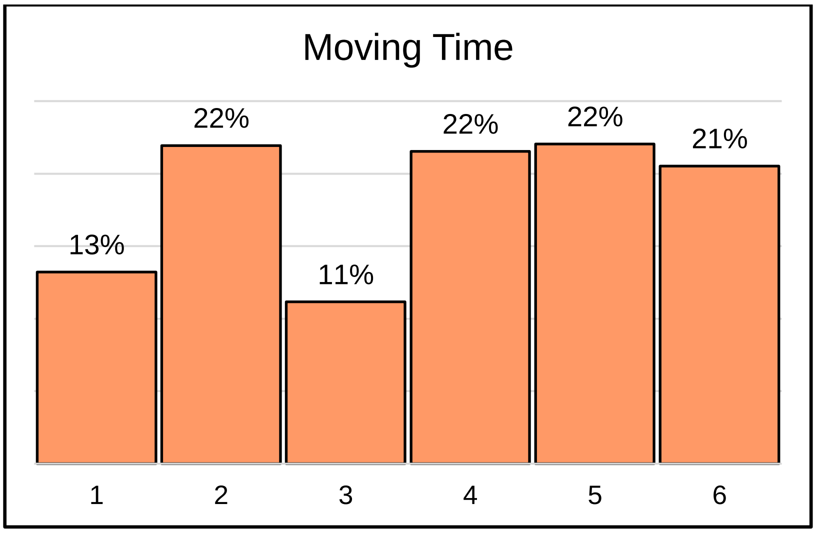

Figure 29. Moving time as a percentage of overall time recorded through six case studies

The overall delay time throughout six case studies varied from 27% to 49% (Figure 30). Delay was broken down into three categories; operational, mechanical and personal. Delay occurred in relation to many site and stand characteristics. The nature and shape of the forest influenced operational delay with respect to relocating WAM and setting up and planning. The undergrowth and vegetation was found to have an impact on mechanical delays, leading to chain issues.

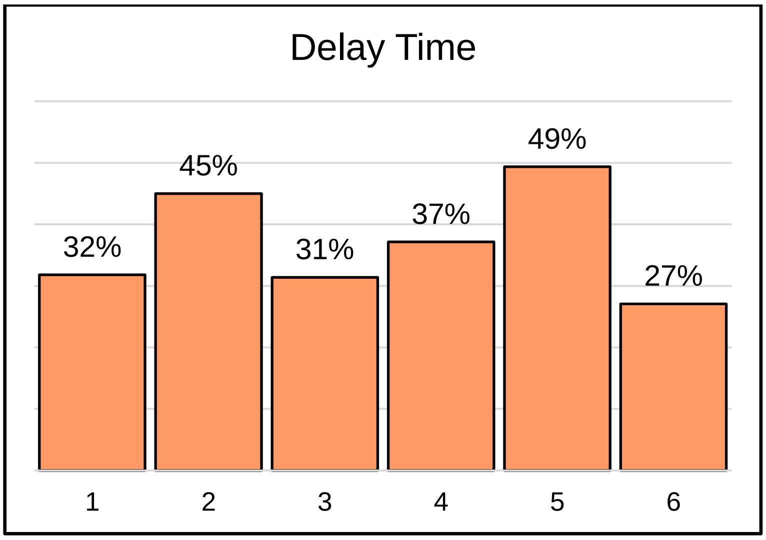

Figure 30. Delay time as a percentage of overall time recorded through six case studies.

The overall shovel time throughout six case studies varied significantly. At three of six studies, shovelling did not occur while attached to the WAM while at case study three, 43% of the time was spent shovelling and attached to the WAM (Figure 31). Case study three involved a ground-based winch-assist operation on a steep hauler block. The nature of the block meant extensive shovelling up slopes of 46 degrees. Shovelling occurred at case study six 15% of time where the operation involved a contract feller felling and shovelling full stems to the road for further extraction by a second independent contractor.

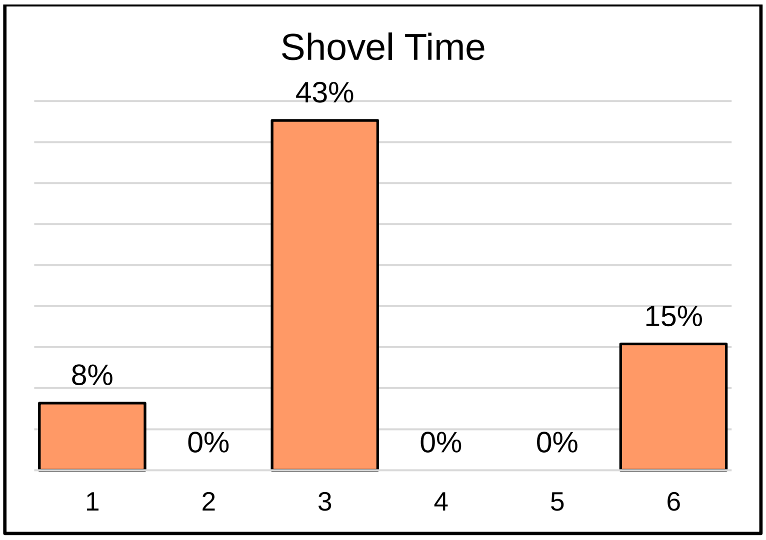

Figure 31. Shovel time as a percentage of overall time recorded through six case studies.

Figure 32 displays all delays observed throughout six case studies and the percentage of overall delay time of each. Three of fourteen delay categories accounted for 60% of delay time; relocate WAM (25%), move setting (20%) and personal delay (15%). Personal delay as discussed is not broken down into subcategories. The next group includes six delay events accounting for 5% to 8%. These being; setting up/planning, chain issues, assisting other operations, filling up with diesel, greasing the machines and maintenance. Assisting other operations included; blasting a skid trail for extraction, fixing processing computer on harvester, aiding new operator with instructions and guidance on the landing and stopping to allow skidder within one tree length. The category of delays occurring less than two % of the total study time included; Radio activity, line handling, warming up, clearing WAM area and working on the felling head.

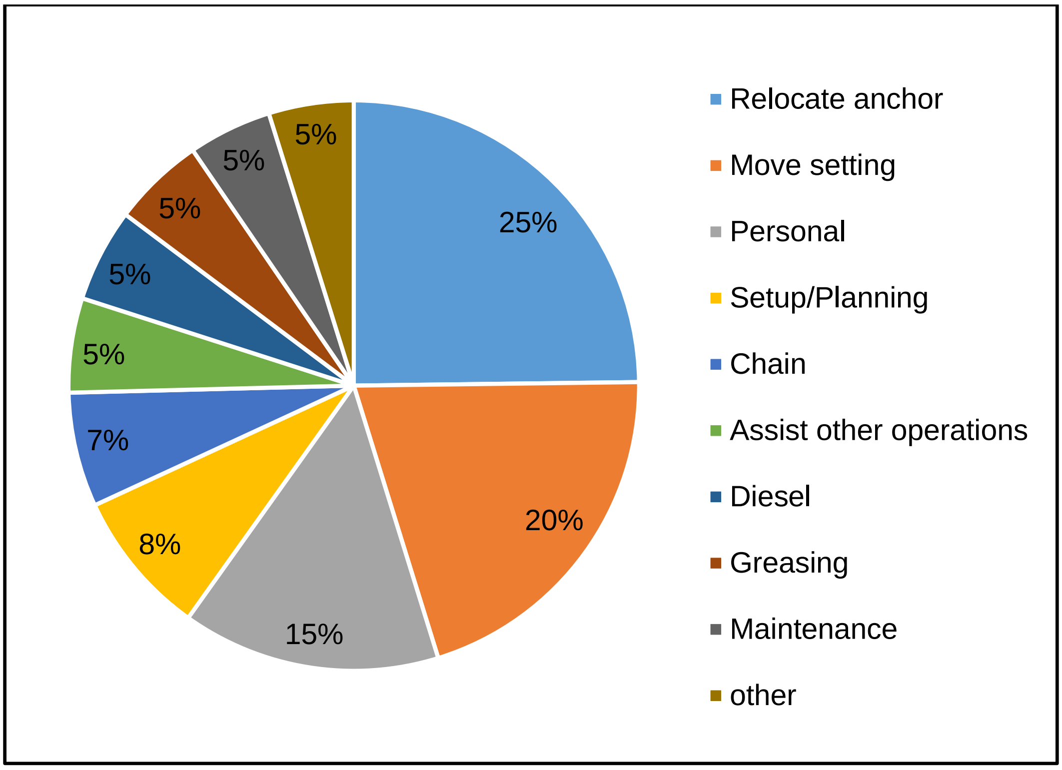

Figure 32. Breakdown of all delays recorded through Six Case Studies.

6.2. Case Study Results and Observations

Case Study One

The majority of operating time at case study one was spent felling (47%), and 32% of the time was delay. Figure 33 below shows the amount of time spent in each category of work. The large amount of time spent felling (47%) was a result of the high stocking per hectare, meaning less time was required moving (13%) between trees. Shovelling (8% on average) occurred for a significant amount of time during one of the days of the study (31%). Shovelling was required to clear stems that were manually felled above a skid trail. Shovelling was required to open access to the end of a skid trail where the next setting for the swing-yarder was to be located.

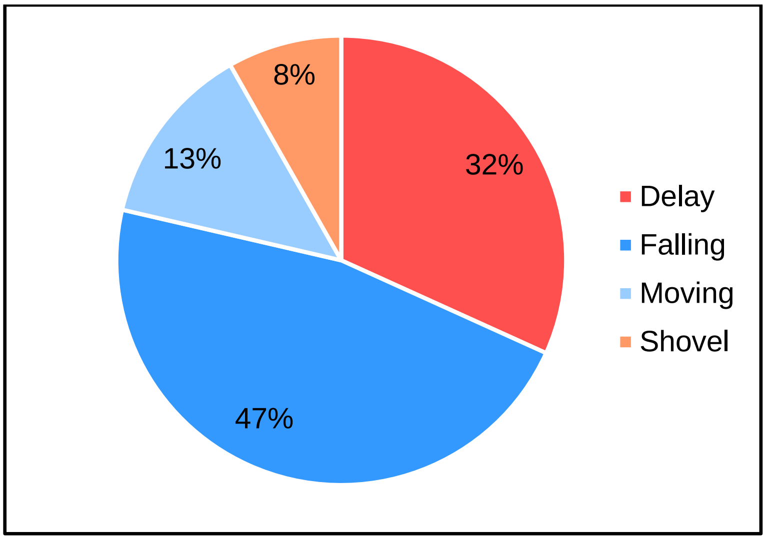

Figure 33. Proportion of operating time at Case Study One.

Delays are common in winch-assist harvesting operations, specifically in regard to moving the WAM and setting up each line (operational delays). Close to half of the delays at Case Study one were operational (45%), followed by personal (36%) and mechanical (19%).

During case study one, 1,296 stems were felled, equating to a volume of 1141m^3. The total amount of time recorded during the study was 1,838 minutes (or 31 hours), resulting in an average productivity of 37.2m^3/SMH. Excluding delays and shovelling, the productivity was 62m^3/PMH. The winch-assist system utilisation rate was 60%, which is the time the SSM was working (felling and moving) and attached to the WAM.

Table 20. Results each day at Case Study One.

Day	Stems	Tonnes	Working + moving (minutes)	Delay (minutes)	Utilisation (%)	(m^3/PMH)	(m^3/SMH)
1	368	323.8	431	126	77%	45.1	34.9
2	332	292.2	259	146	64%	67.7	43.3
3	324	285.1	213	272	44%	80.3	35.3
4	272	239.4	200	191	51%	71.8	36.7
Total	1296	1140.5	1103	735	60%	62.0	37.2

The WAM operator was experienced, having operated a SSM over the past five years. Although the operator had spent a lot of time working in SSMs, operating with winch-assist was a relatively new task. The operator had only seven months' experience operating the WAM.

A commonly raised topic in discussion was the method of felling when 'winch-assisted'. The operator and other crew members highlighted that there was no set method, as it depends entirely on site and stand conditions.

It was observed that the operation was very safety conscious. Two daily safety forms were filled out by the operator, the first being a daily checklist, ensuring both the WAM and SSM were inspected before operating each day. The second form was a mechanised felling plan, where the operator identified any hazards in the felling area for the day and how they are controlled.

A noticeable impact on productivity was the length of each felling corridor and the number of WAM shifts. When the corridor was short, more operational delays occurred moving the WAM. An interesting observation was that each time the WAM was shifted, it was moved 50 – 100m along the track. Moving the WAM longer distance helped to minimise the number of WAM shifts and increase utilisation. A long shifting distance resulted in standing trees being used to redirect the rope when starting a new line. The operator mentioned that having a second track above the tree face or having the ability to position the WAM well above the tree face could decrease operational delay. A second track increases the area able to be harvested before moving the WAM. An example of a second track can be seen in Figure 34. It must be noted that the primary purpose of this track was access for the swing yarder tail hold machine.

Figure 34. Second track that could be used for the WAM: Case Study One.

Winch-assist harvesting systems are a higher cost than a manual felling crew, although using a machine to fell and bunch trees increases the productivity of the next process in the harvesting system. For example, the SSM in this operation laid stems across the slope in bunches of two or three, providing a significant improvement to the productivity of the cable yarder.

Case Study Two

At case study two, 29% of time was spent felling and 20% of the time moving (Figure 35). These result are due to the relatively low stocking at case study two. Shovelling (14%) took place when slopes were blind to the swing yarder or occurred when felling took place beside the stream. When felling beside the stream, the SSM detached from the WAM to shovel the basins (Figure 36).

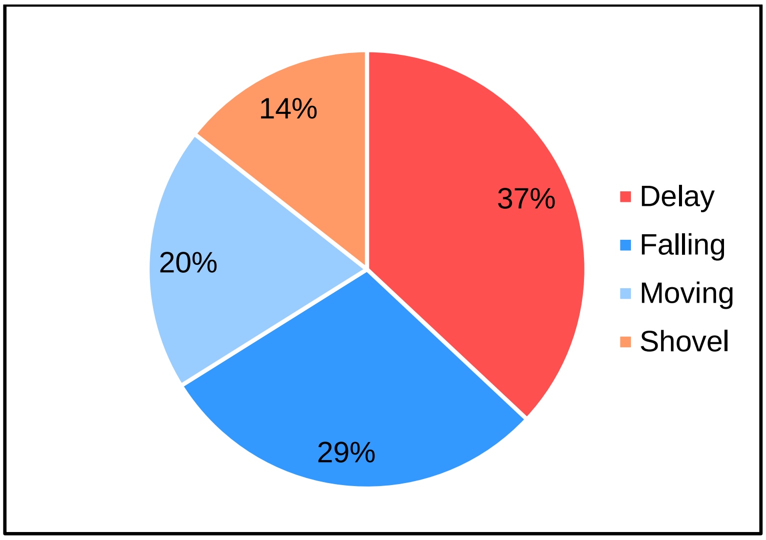

Figure 35. Proportion of operating time at Case Study Two.

The largest proportion of operating time throughout the week was delay (37%). The majority of delays were operational (76%). Operational delays are defined as the system being available to 'work', but are being held up by other parts of the operation. In this case, moving the WAM was the most significant operational delay. WAM shifts occurred more frequently when the area of harvest changed and corridor lengths were shorter.

Mechanical delays (21%) occurred mainly because of bar and chain problems, specifically changing blunt chains. Only three % of delays were personal, meaning that the operator did not take long breaks and (or) was good at multi-tasking. For example, taking phone calls while operating and eating food during other delay periods.

Figure 36. John Deere 909MH SSM next to shovelled stems at Case Study Two.

At case study two, 707 stems were felled, equating to a volume of 1,577m^3. The total amount of time recorded was 1,628 minutes (or 27 hours), resulting in a productivity of 58.1m^3/SMH. Excluding delays, productivity was 102m^3/PMH. On one day, the productivity was 114m^3/PMH as a result of suitable felling conditions such as long even slopes and large piece size (Figure 37). The winch-assist harvesting system utilisation rate was 57% at case study two.

Figure 37. Site conditions that yielded the highest productivity at Case Study two.

Table 21. Results each day at Case Study Two.

Day	Stems	Tonnes	Working + moving (minutes)	Delay (minutes)	Utilisation (%)	(m^3/PMH)	(m^3/SMH)
1	226	504.0	267	120	69%	113.3	78.1
2	217	483.9	291	231	56%	99.8	55.6
3	162	361.3	212	159	57%	102.2	58.4
4	102	227.5	157	191	45%	86.9	39.2
Total	707	1576.6	927	701	57%	102	58.1

During case study two the difficulty of felling increased over the week. The terrain changed from long even slopes to short slopes directly leading into a stream. Harvesting near streams requires significant care in respect to protecting riparian zones and watercourses. The solution for this area, was to pull stems away from the river back into the cutover, which took more time. Shortly after beginning this process, the operation was called off as there was a high chance stems would slide into the stream. The terrain was difficult and dangerous for the WAM, having several rocky bluffs through the middle of the slope. The shovelling process would have been slow and costly if this had gone ahead. This setting can be seen in Figure 38 below.

Figure 38. ROB WAM and John Deere 909MH SSM: Case study Two.

Where slopes were blind to the swing yarder operator or sufficient deflection could not be achieved, shovelling to a visible destination took place creating a surge pile for extraction. This slowed the productivity of the WA system, although it helped to increase the overall productivity of the operation. The large piece size at case study two meant there was no need to bunch for extraction.

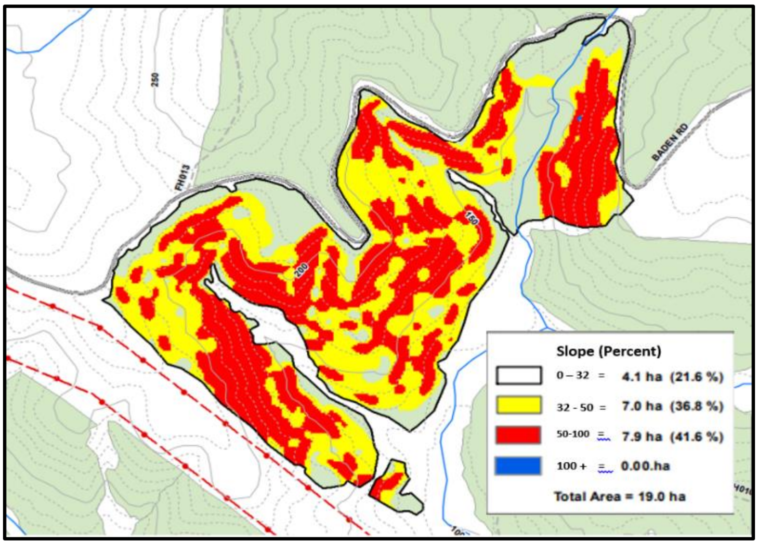

Figure 39. Slope map at Case Study Two.

The operator at study site two was the owner of the harvesting crew. Being the owner of a logging crew gives a greater incentive to ensure production targets are being met and machines are operating to their full capacity.

Case Study Three

At case study three, 15% of the time was spent felling, 7% moving and 31% was due to delays (Figure 40). Shovelling (47%) was the most significant proportion of operating time. Stems were felled into gullies where shovelling upslope was easier and other excavators on-site helped with extraction (Figure 41). Where possible, the SSM detached from the WAM to shovel basins.

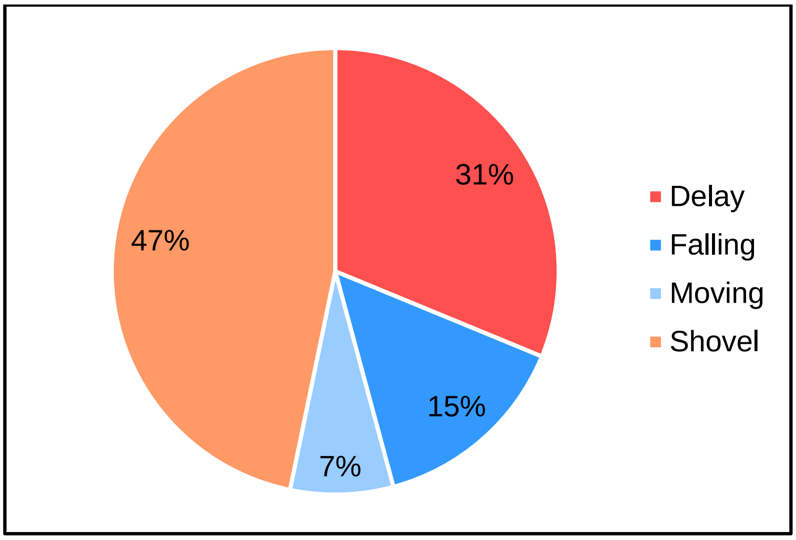

Figure 40. Proportion of operating time at Case Study Three.


Figure 41. Komatsu PC270 assisting Tigercat LS855C with shovel extraction at Case Study Three. (winch wire rope highlighted in red).

Delay contributed to 31% of the time throughout the week. The majority of delays were operational (49%). Operational delays are defined as the system being available to 'work' but are being held up by other parts of the operation. In this case, moving the WAM was the most significant operational delay. Mechanical delays (38%) occurred due to bar, chain and wire rope problems; specifically putting the chain on the bar after it slipping off. Personal delay (13%) was due to lunch breaks.

During the study period, 117 trees were felled, equating to a volume of 222m^3. The total amount of time recording took place was 1,253 minutes (or 21 hours) resulting in a productivity of 10.6m^3/SMH. Excluding delays, productivity was 41.9m^3/PMH. The winch-assist harvesting system utilisation rate was 25%, which is the time the SSM was working (felling and moving) and attached to the WAM.

Table 22. Results each day at Case Study Three.

Day	Stems	Tonnes	Working + moving (minutes)	Delay (minutes)	Utilisation (%)	(m^3/PMH)	(m^3/SMH)
1	26	49.4	65	291	18%	45.6	8.3
2	44	83.6	102	334	23%	49.2	11.5
3	19	36.1	110	128	46%	19.7	9.1
4	28	53.2	41	182	18%	77.9	14.3
Total	117	222.3	318	935	25%	41.9	10.6

The system observed at case study three involved winch-assist felling and shovelling on a steep hauler setting. The system would normally implement a swing yarder for extraction however, a number of factors prevented this; the swing yarder was under maintenance, the setting had poor deflection, the nature of the block was dangerous and unsafe for manual breaking out and the undergrowth was thick and unsafe for manual felling.

The undergrowth at case study three was brushed and relocated away from the shovelling path. Stems shovelled up slope are more likely to slide down slope if woody debris are on the ground (Figure 42).

Figure 42. Tigercat LS855C SSM next to undergrowth (average height of 5m): Case Study Three.

Case study three was a challenging setting often requiring three excavators working together on the slope (Figure 44). The SSM shovelled stems to an area safe for a conventional excavator. The excavator closest to SSM commonly cut a bench into the slope, allowing safer shovelling.

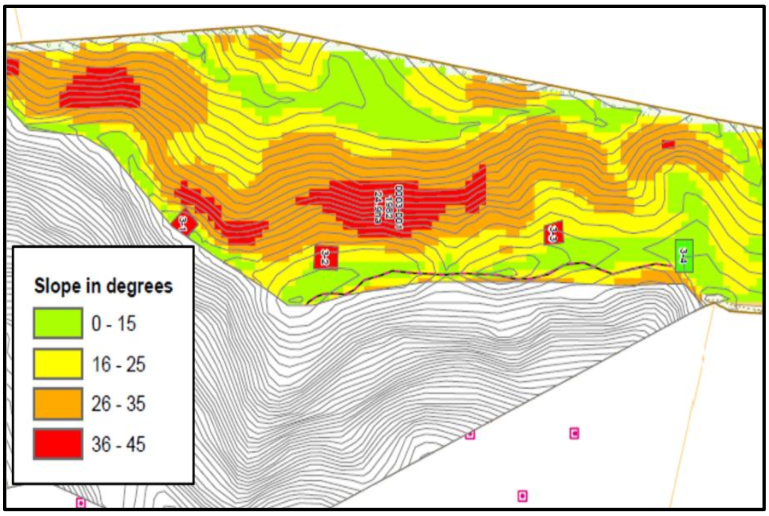

Figure 43. Slope map at Case Study Three.


Figure 44. Site conditions showing three excavators working together at Case Study Three.

The steep slopes and rocky outcrops at case study three led to wire rope failure (Figure 45). The wire rope damage caused a large mechanical delay, halting operations for the day requiring a mechanic to be called out and repair the wire rope.


Figure 45. Wire rope fatigue caused from repetitive use on steep slopes and rocky outcrops: Case Study Three.

Case Study Four

At case study four, 38% of the time was spent felling, 19% of the time was spent moving and 43% was due to delays (Figure 46). The high percentage of delays was influenced by the relatively short corridor lengths, which required more WAM shifts and line handling. The majority of delays were operational (86%), defined as the system being available to 'work' but held up by other parts of the operation. Moving the WAM was the most significant operational delay, followed by walking the WAM and SSM to the block entrance to refuel. WAM shifts occurred more frequently when the corridor lengths decreased in narrow areas of the setting. Mechanical delays (13%) occurred because of hydraulic hose issues. The operator rarely stopped working, resulting in only 1% of personal delay.

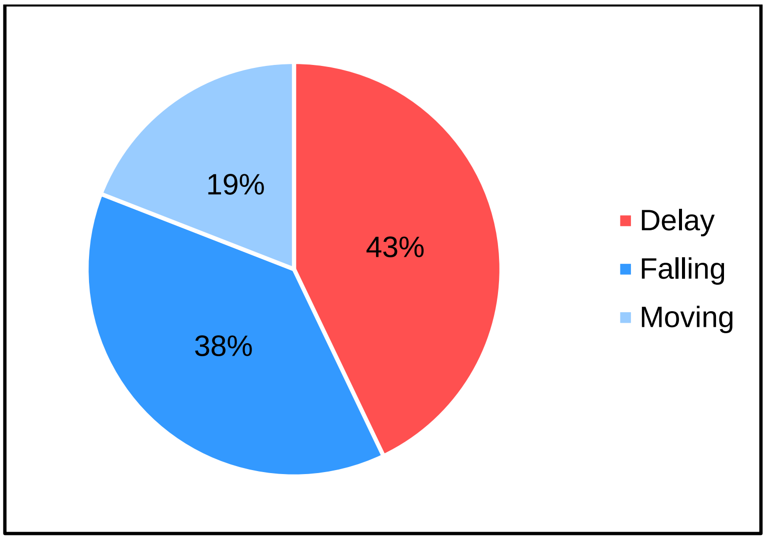

Figure 46. Proportion of operating time at Case Study Four.

During the study period, 755 trees were felled. The piece size was 0.7m^3 equating to a volume of 528.5m^3. The total amount of time recording took place was 850 minutes (or) 14 hours, resulting in a productivity of 37.3m^3/SMH. The productivity was 59.4m^3/PMH when only taking into account moving and felling.

During this short-term study, the utilisation rate of the winch-assist harvesting system was 63% when the SSM was working and tethered to the EMS WAM (both machines working together).

Table 23. Results each day at Case Study Four.

Day	Stems	Tonnes	Working + moving (minutes)	Delay (minutes)	Utilisation (%)	(m^3/PMH)	(m^3/SMH)
1	332	232.4	199	104	66%	70.1	46.0
2	188	131.6	122	68	64%	64.7	41.6
3	235	164.5	213	144	60%	46.3	27.6
Total	755	528.5	534	316	63%	59.4	37.3

Winch-assist has recently been integrated into the harvesting system at case study four to allow more forest area to be accessed by machines. The SSM was winched down the slope felling and bunching trees while travelling both uphill and downhill. The extraction phase will use a self-levelling excavator winched down the same slope, shovelling to a skid trail at the bottom of the block where a skidder can gain access (Figure 47).

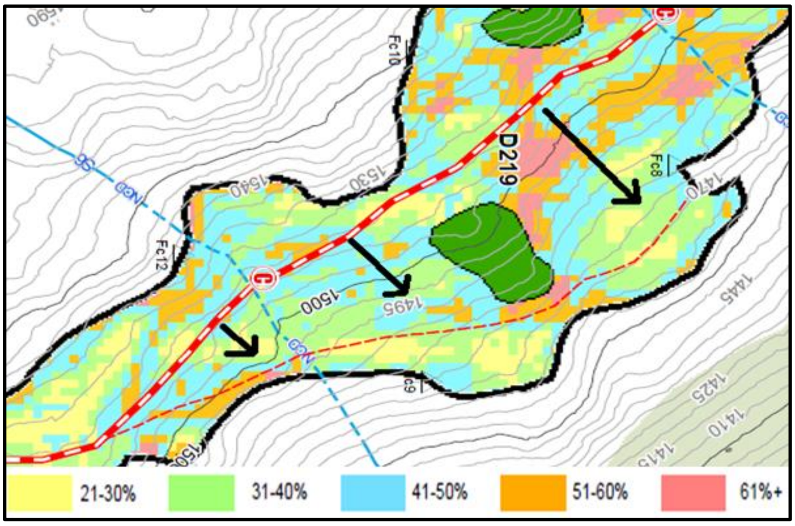

Figure 47. Slope map displaying the main access road, skid trail and direction of shovelling at Case Study Four.

The amount of WAM shifts most significantly affected productivity. For example, on the third day of the study, 46% of the time was delay and a large proportion of this was relocating the WAM. One consideration might be the use of a second person to operate the WAM to speed up this task when working in short corridors. Other delays observed throughout the study were; slashing wet areas, line handling, radio communication, refuelling, replacing a hose and poor visibility from snowfall.

Figure 48. Tigercat L870C and EMS traction line working at Case Study Four.

The stand was variable with mixed species and age class, with four species DBH ranging from 15cm to 83cm. The continuous rotating bunching saw appeared to suit these conditions well; being able to brush, and having the ability to fell multiple stems in a single cycle. More than one tree was felled in 26% of cycles. Double cuts were required on larger trees; one cut below, and a second from above.

Mechanical delays were not common, having new equipment and regular servicing. Bunching saws require less maintenance than feller directors do as they do not have a bar and chain (Figure 49).

Figure 49. Tigercat 5702 continuous rotating hot saw: Case study Four.

Slashing was required in multiple areas at case study four, where the soil was wet and the risk of excessive machine disturbance was high.

Case Study Five

At case study five, 29% of the time was spent felling, 22% of the time was spent moving and 48% was due to delays (Figure 50). During this study, the delay was found to be a result of the natural terrain, leading to more frequent WAM shifts and areas where untethered felling took place (flat benches). Delays observed were moving setting, relocating the WAM, refuelling, line handling, mechanical breakdowns, and personal delay.

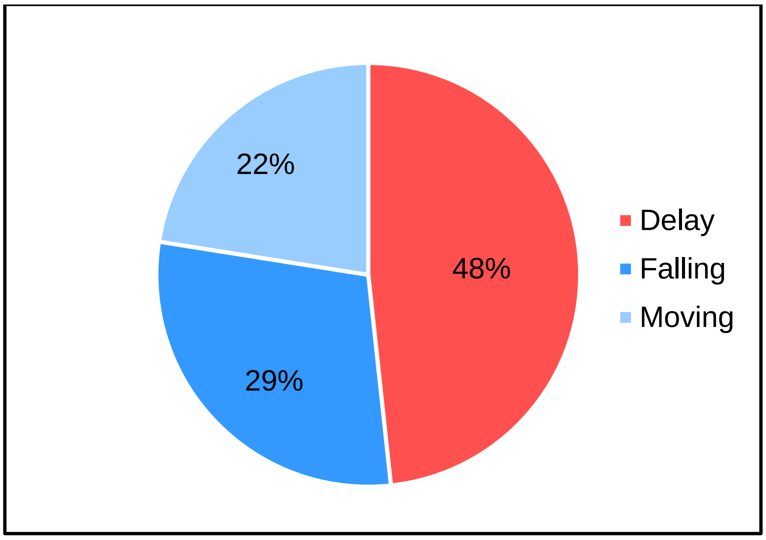

Figure 50. Proportion of operating time throughout the time study at Case Study Five.

During the four-day study period, 823 trees were felled. The average piece size throughout the three sites was 0.71m^3 equating to a volume of 593m^3. The total study time was 1058 minutes (or

18 hours), giving a productivity of $34m^3$/SMH. The productivity was $66m^3$/PMH when only considering moving and felling. Time not analysed was a result of poor vision and researcher delay; setting up, sampling standing trees and communicating with the operator.

Table 24. Results each day at Case Study Five.

Day	Stems	Tonnes	Working + moving (minutes)	Delay (minutes)	Utilisation (%)	(m^3/PMH)	(m^3/SMH)
1	127	64	93	119	44%	41.0	18.0
2	280	207	170	204	45%	73.1	33.2
3	118	87	78	34	70%	67.2	46.8
4	298	235	195	165	54%	72.4	39.2
Total	823	593	536	522	51%	66.4	33.7

The utilisation rate when the SSM was working and tethered to the FFE WAM (both machines working together) was 51%. During the time study, the operator mentioned that the winch-assist harvesting system is often utilised less than 50% of time. The low utilisation is due to the nature of the terrain in the cut-blocks and some slopes being less than 50% gradient and not requiring winch-assist.

The operator at case study five prefers felling when moving upslope, allowing a lower stump and more merchantable volume to be cut. The centre of gravity is at optimum when the felling head is uphill. The average slope on day one was 73% with rocky outcrops present and a corridor length no greater than 100 metres. The slope at setting two was 67% with slightly longer corridor lengths. When felling landings, roadside, benches or gullies, the WAM would shut down and felling would take place not attached to the wire rope.

On the second day, three hours and 30 minutes was required to move both machines to a new setting. Figure 51 shows the Falcon WAM ready to shift setting. The new setting required untethered harvesting to take place; clearing skid roads and felling trees close to the road.

Figure 51. The Falcon WAM moving setting at Case Study Five.

To avoid the risk of damage to the winch line when moving the line over stumps or obstacles, the operator stopped the hot saw quickly turning off the hydraulic flow and cutting part way into a larger stump.

An interesting observation was to ‘Pack’ full stems to the bottom or top of the slope (Figure 52). Packing is extracting stems to either the top or bottom of the slope where a skidder can reach them. Packing occurred when corridor lengths were less than 100m.

A Tigercat 632E skidder from either the top or the bottom of the slope carried out the extraction phase at case study five, where lower gradient slopes allow safe access. The operator mentioned that if possible (or) if a pre-existing road is located on the slope, a skid road can be constructed for extraction.

Figure 52. Tigercat LX870D SSM packing a stem to the bottom of the corridor: Case Study Five.

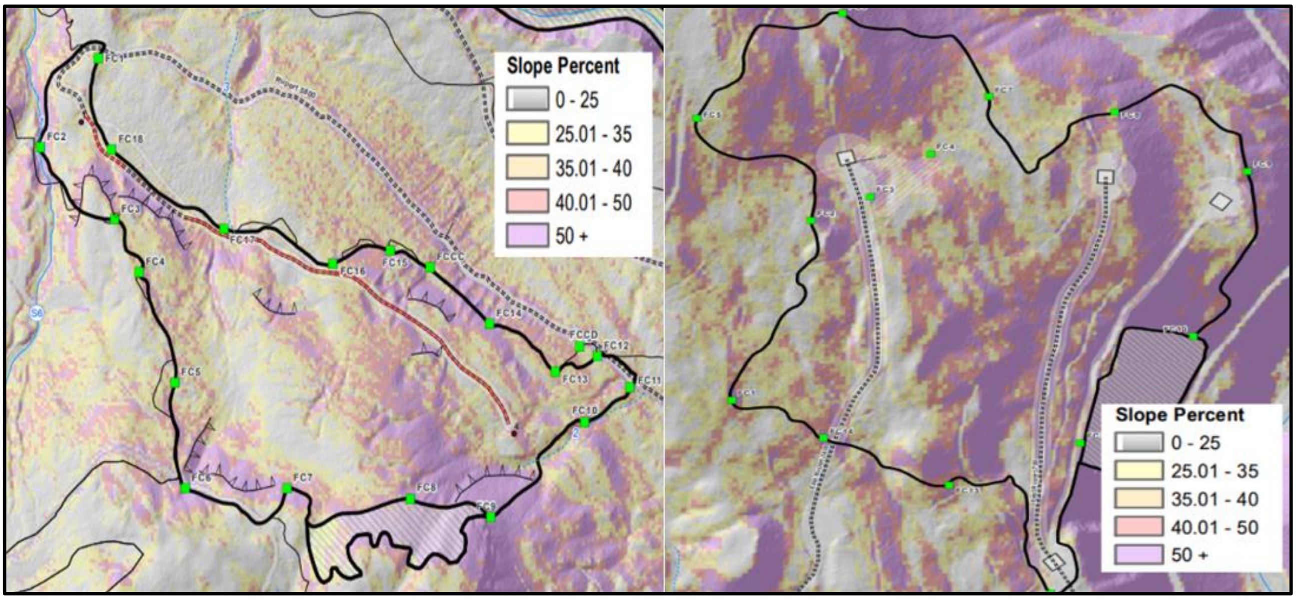

Figure 53. Slope maps at Case Study Five (block 79 and 78*).*

Case Study Six

At case study six, 37% of the time was spent felling, 21% of the time was spent moving, 15% of the time was spent shovelling attached to the winch and 27% was due to delays (Figure 54). During this study, delay was found to be a result of moving site, relocating the WAM, refuelling, line handling, mechanical breakdowns, operational delay and personal delay.

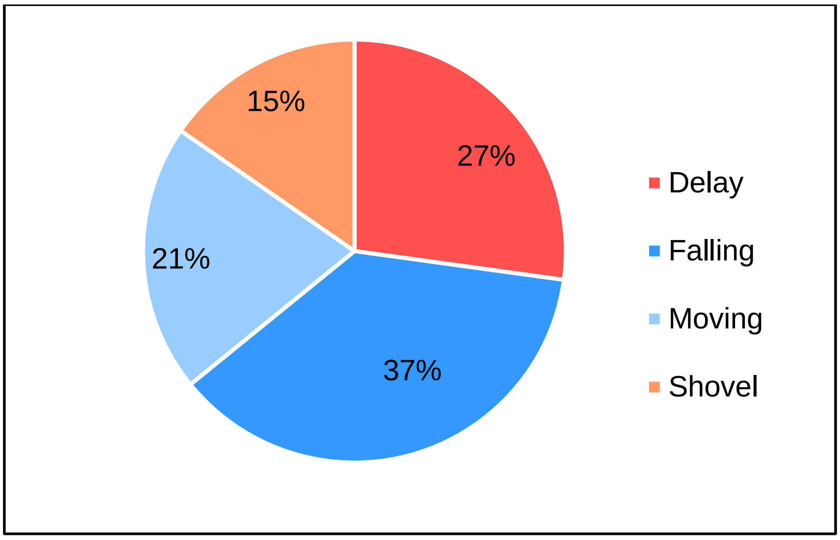

Figure 54. Proportion of operating time throughout the time study at Case Study Six.

During the study period, 638 trees were felled. The piece size was 0.41m^3 equating to a volume of 262m^3. The total amount of time recording took place was 797 minutes or 13.3 hours, giving a productivity of 20m^3/SMH. The productivity was 34m^3/PMH when only taking into account Moving and felling. The utilisation rate of the winch-assist harvesting system when the SSM was felling, moving and tethered to the FFE WAM (both machines working together) was 58%.

Table 25. Results each day at Case Study Six.

Day	Stems	Tonnes	Working + moving (minutes)	Delay (minutes)	Utilisation (%)	(m^3/PMH)	(m^3/SMH)
1	377	154.57	248	113	69%	37.4	25.7
2	261	107.01	210	226	48%	30.6	14.7
Total	638	261.58	458	339	57%	34.3	19.7

The harvest system observed was a steep slope winch- assist ground-based operation. This system has a high utilisation as it is solely a winch-assist harvesting crew with two machines whereby it works only in winch-assist required terrain. The slope lengths observed were between 80 and 120 metres (Figure 55), and the method of extraction involved felling and shovelling in the same process. Extraction took place as the SSM made its way down the slope, felling up to ten trees before shovelling these stems 30 m to the next heap and repeating.

Figure 55. Slope at Case Study Six.

The SSM was equipped with a heel, improving the shovelling phase substantially (Figure 56). At the end of the corridor, a large surge pile awaits extraction or processing by another logging company.

Figure 56. Cat 552 applying the heel while shovelling: Case Study Six.

The average slope was 35% and did not always require winch-assist however sharp pitches of up to 80% were common requiring winch-assist. The snow was measured at a depth between one to two metres, which created another variable to deal with on the slope. In response to the snow conditions, aftermarket spikes have been welded to the SSMs grouses. The ROB WAM also had four spikes attached to the bottom side of the blade to ensure WAM stability (Figure 57).

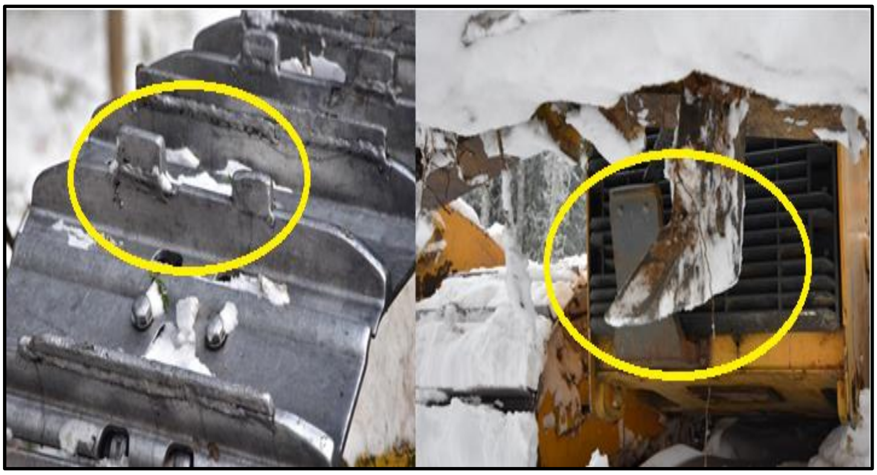

Figure 57. Traction solution to snow: Case Study 6.

The operator mentioned that snow not only decreases traction capability, it also causes ice build-up within the felling head. Snow/ice build-up causes less flexibility for hydraulic hoses and therefore leading to mechanical issues within the felling head.

A high utilisation of 90% existed on the first day as the WAM was already setup ready to operate, did not require refuelling, no mechanical delay occurred and only one WAM shift took place. Note that this utilisation did not include the first hour of operating before arriving on site. The first hour often involves warming up the WAM and SSM, ensuring everything is mechanically sound and the operator preparing any paperwork for the day.

From a researcher's point of view, the high utilisation was a result of frequently using catch trees to limit the number of WAM shifts (Figure 58). The operator commented that three or four corridors are commonly achieved per WAM shift. The number of WAM shifts depend entirely on the nature of the block and the existence of suitable catch trees.

Figure 58. Example of a catch tree in use at Case Study Six.

The narrow tracks used for WAM locations proved difficult for manoeuvring and relocating the WAM. The narrow track also contributed to using catch trees. It was observed during the study that the WAM reversed into a bank in a tight location, slightly damaging the exterior of the machine.

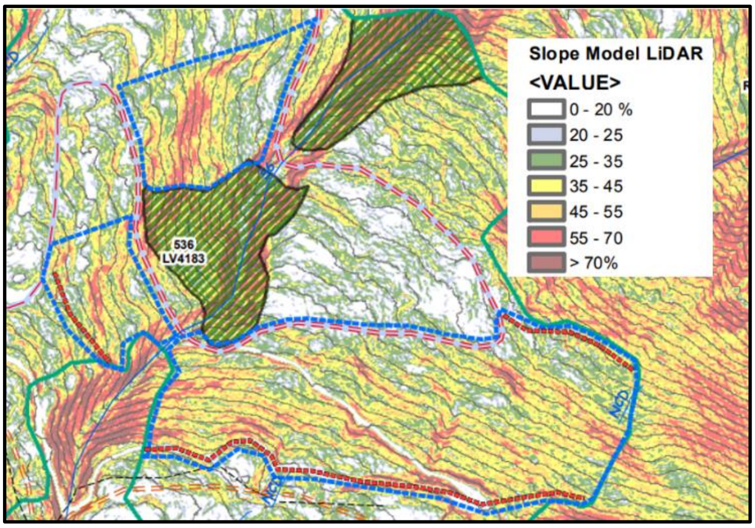

Figure 59. Slope map at Case Study Six (areas bordered in blue were planned for winch-assist).

7. Analysis of grouped data

The data presented below is a summary of the six case studies, displaying all recorded measurements and results each day. Species is classed as either 0 or 1, where 0 is mono species and 1 is multi species. Soil and site data were valued 1 – 3 depending on the classification each day (see tables 2 and 3 in materials and methods). The corridor and slope measurements were recorded as the average value each day. Stocking and piece size were provided by the respective forest management company as recorded by prior inventory measurement. Utilisation was recorded as the percentage of productive time against total time and productivity was recorded using the number of stems felled multiplied by the piece size.

Table 26. Total data overview recorded through six case studies.

Crew	Species	Soil	Site	Corridor (m)	Slope (%)	Stocking (sph)	Piece size (m^3)	Utilisation (%)	Productivity (m^3/ha)
Button	0	3	3	270	44	757	0.88	77.4	45.1
Button	0	2	2	255	47	757	0.88	63.9	67.7
Button	0	2	1	240	50	757	0.88	43.9	80.3
Button	0	2	2	75	60	757	0.88	51.2	71.8
Gamble	0	1	1	166	45	278	2.23	68.9	113.3
Gamble	0	2	1	166	40	278	2.23	55.7	99.8
Gamble	0	2	1	148	30	278	2.23	57.1	102.2
Gamble	0	2	2	55	60	278	2.23	45.1	86.9
Mold	0	3	3	201	75	320	1.9	18.3	45.6
Mold	0	3	3	171	82	320	1.9	23.4	49.2
Mold	0	3	3	157	84	320	1.9	46.2	19.7
Mold	0	2	3	155	81	320	1.9	18.4	77.9
Wadlegger	1	3	2	75	45	423	0.7	65.7	70.1
Wadlegger	1	3	2	51	39	423	0.7	64.2	64.7
Wadlegger	1	2	3	37	35	423	0.7	59.7	46.3
Lime Creek	1	3	3	92	64	575	0.5	43.9	40.9
Lime Creek	1	1	2	100	65	368	0.74	45.5	73.1
Lime Creek	1	2	2	80	61	368	0.74	69.6	67.2
Lime Creek	1	2	2	65	51	450	0.79	54.2	72.4
Gorge Creek	1	2	2	87	28	890	0.41	68.7	37.4
Gorge Creek	1	3	2	93	32	890	0.41	48.2	30.6

For both productivity and utilisation, stepwise regression was carried out using the software R commander. The stepwise regression consists of iteratively adding and removing predictors in the predictive model. This method helps to find the subset of variables in the data set resulting in the best performing model.

The stepwise regression output recorded a p-value of less than 0.05 indicating a strong relationship between chosen variables with productivity and utilisation. Not all variables were linearly independent and therefore were not statistically significant. The information of the variables that were not statistically significant were already contained in the other variables.

Table 27. List of factors used in equations one and two.

Factors			
Species	Mono (0)	Multi (1)	
Soil Class	Good (1)	Medium (2)	Bad (3)
Site Difficulty	Easy (1)	Medium (2)	Difficult (3)
Variable factors			
Slope			
Stocking			
Piece Size			

Productivity

Equation 1 models the productive machine hour productivity of winch-assist harvesting systems. The significant factors determined through stepwise regression are either factors (0,1,2,3) or variable. The factor variables are Species, Soil and Site. The variables are Stocking and Piece size.

When the model used mono species, medium soil class, medium site difficulty, average stocking of 487 stems per hectare and an average piece size of 1.23m^3, it calculated a winch-assist productivity of 79m^3/PMH. The model calculated a productivity of 56m^3/PMH when using multi species. The output values from the model are similar to the observed winch-assist productivity.

The R^2 value of 79% and residual standard error of 11.31m^3 indicates the model has sufficient accuracy. The distribution of residuals was considered sufficiently normal and did not require transformation.

Table 28. Factors and coefficients for productivity of winch-assist harvesting systems.

Factors	P value	Coefficients
Intercept	>0.001	195
Species	0.074	-23
Soil	0.058	-9.9
Site	>0.001	-21
Stocking	0.020	-0.07
Piece Size	0.218	-16
R squared value	79%	

Equation 1. Productive machine hour productivity of winch-assist harvesting system model

$$Productivity\ (\mathrm{m^3/PMH}) = 195 - 23 * Species - 10 * Soil\ Type - 21 * Site\ difficulty - 0.07 * Stocking - 16 * Piece\ Size$$

Utilisation

Equation 2 models the utilisation of winch-assist harvesting systems. The significant factors determined through stepwise regression are either factors (0,1,2,3) or variable. The factor variables are Species, Soil and Site. The variables are Stocking and Piece size.

When the model used mono species, average slope of 53%, average stocking of 487 stems per hectare and the average piece size of $1.23m^3$, it calculated a winch-assist utilisation of 58%. This value is similar and follows the same pattern as the recorded average utilisation of 52%.

TheR^2 value of 50% and residual standard error of $12m^3$/pmh indicates the model has alright but not sufficient accuracy. The distribution of residuals was considered sufficiently normal and did not require transformation.

Table 29. Factors and coefficients for utilisation of winch-assist harvesting systems.

Factors	P value	Coefficients
Intercept	0.002	155
Species	0.163	-20
Slope	>0.001	-0.8
Stocking	0.123	-0.05
Piece size	0.087	-24
R squared value	50%	

Equation 2. Utilisation of winch-assist harvesting system model

$$Utilisation\ (\%) = 155 - 20 * Species - 0.8 * Slope - 0.05 * Stocking - 24 * Piece\ Size$$

8. Discussion

In New Zealand, WAM units are usually palced on landings, or larger areas are cleared to make space. However, case study three showed that the WAM can be located on narrow tracks. Narrow tracks can be constructed at a lower cost with the WAM, however they create the risk of the machine sliding off the track or bumping into the bank. In the case of utilising small, narrow tracks, installing aftermarket reverse cameras to ensure that the operator has a clear view of the rear of the WAM during relocations is recommended. Reversing cameras could help reduce the time required to relocate the WAM, minimise the risk of damage to winches (and equipment) during moves in tight locations, and may improve safety.

The most common operational delay observed was relocating the WAM. Relocating the WAM 91% of the time required the operator to exit the SSM and operate the WAM. At case study four, a second person was available to move the WAM 45 % of the study time, equating to the other 9% of total WAM relocations. The corridor length was a large contributor to the number of relocations per day. The longest corridor length observed was 270 m at case study one and the shortest of 37 m was observed at case study four. The short corridor length at case study four led to a second person relocating the WAM to decrease this delay

Undergrowth and cutover was found to have the largest affect on relocating the WAM as the operator had to climb over slash and debris. Relocating the WAM occurred 53 times over the six case studies. The average time required to relocate the WAM was twelve minutes and 15 seconds, the maximum time was 70 minutes and 49 seconds, and the minimum time required was two minutes.

To optimize winch-assist harvesting system utilisation and decrease the number of WAM relocations, the contractor could consider using standing trees or high stumps as catch trees. This technique should allow the WAM to face along the track while the SSM redirects (binds around a stump) the line (Figure 60). When the catch tree technique is possible, it can help minimise WAM relocations and keep the WAM further away from felling operations. To take advantage of large high stumps on the road right of ways, harvest planners and road construction crews should identify the need for high stumps and leave them to provide options for the winch-assist operation.

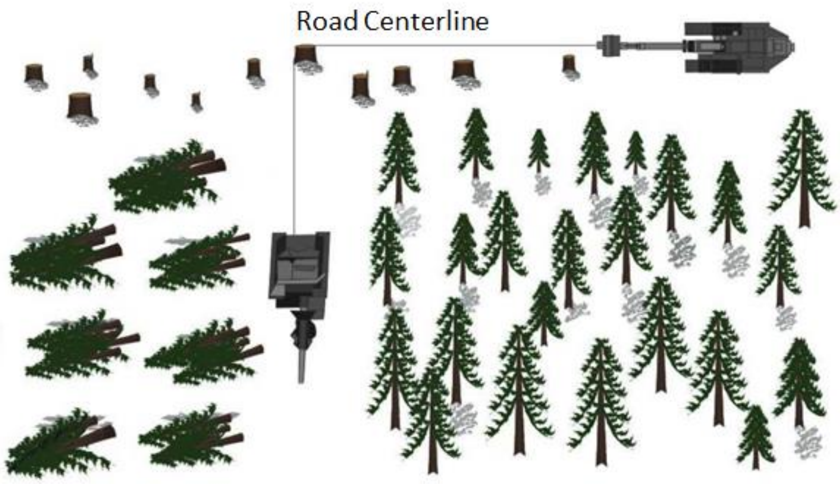

Figure 60. Example of a catch tree being used (WAM located on a narrow ridge).

Winch-assist can be adapted to harvesting systems in numerous ways: ground-based, cable-based or a mixture. The winch-assist harvesting systems observed throughout the six studies were related to the site and stand conditions. The SSM was often used for felling as well as extraction; however, the form of extraction varied between each case study. Winch-assist extraction at case study three shared the same importance as felling. The shared importance meant a large proportion (43%) of time was spent shovelling. Shovelling had a large impact on utilisation and the overall productivity observed throughout the case study.

In New Zealand It is not common for more than one SSM to utilise the WAM. However, at case study four, a second grapple SSM utilised winch-assist on the slope after felling was complete. The purpose of the second SSM was shovelling stems on average 54 m to a track for skidder extraction, breaking up the felling and shovelling phases. Similar site and stand conditions were observed at case study six, however, the SSM felled and shovelled on average 90 m. The productivity at case study four was 60m^3/pmh in comparison to 34m^3/pmh at case study six, totalling a 26m^3/pmh difference in productivity. This advises that breaking up the felling and extraction phases increases productivity, although it is not always possible and is also a much greater cost.

While observing operations at case study five, the SSM continued to fell and extract a flat, mid-slope bench not attached to the wire rope, while the WAM was left to idle for greater than an hour. It is important that the WAM is shut down (remotely) during such times (provided the remote start is reliable) so that:

- Unnecessary hours are not added to the machine's operating time which reduces re-sale value.
- Machine time is used for productivity and is not increased unnecessarily which impacts warranty hours and increased machine servicing (based on non-productive time).
- Fuel efficiency is promoted, and carbon footprint is reduced.

On average, personal delay in Canada was lower than observed in New Zealand. The lower personal delay was a factor of the extreme seasons and the time of year the study took place; sunlight hours were less than usual, meaning shorter workdays. Shorter workdays meant less personal delay. New Zealand operators usually work 10-12 hours having up to an hour break throughout this time. The shorter workdays also affected fixed delays such as planning. The shorter workdays in some cases may have created a misrepresentation. Personal delay accounted for 14% of all delays.

Through the six case studies mechanical delay accounted for 17% of all delays. The case study with the highest amount of mechanical delay was case study three (38% of total delay time), while at case study five, 2% of the total delay time was mechanical. The thick understory at case study three caused complications with the chain and bar; when felling, small stems would often get caught between the tree being felled and the bar, causing chain damage or flicking the chain off.

The stand factor found to influence productivity most was piece size. The piece size at case study six was 0.41m^3 resulting in a productivity of 34m^3/pmh. The piece size at case study two was 2.2m^3 resulting in a productivity of 102m^3/pmh.

9. Conclusion

Winch-assist felling and extraction operations differ considerably to traditional felling and yarding on steep slopes. The technology and our understanding of planning and implementation has developed rapidly over the last ten years. Harvest planners and forest managers must understand winch-assist requirements to maximise the value from this new approach to felling and extraction. It should not be considered as the same operation, from a planning and layout perspective.

Given the cost of winch-assist harvesting systems, it would be financially beneficial to all parties to ensure harvest planners are provided feedback from contractors as to how layout impacts harvest operations. Feedback will help to ensure the harvest plan meets the contractor's needs and maximises the benefit of winch-assist operations.

Winch-assist harvesting systems are a higher cost than a manual felling system, although using a machine to fell and bunch trees increases the productivity of the next process in the harvesting system.

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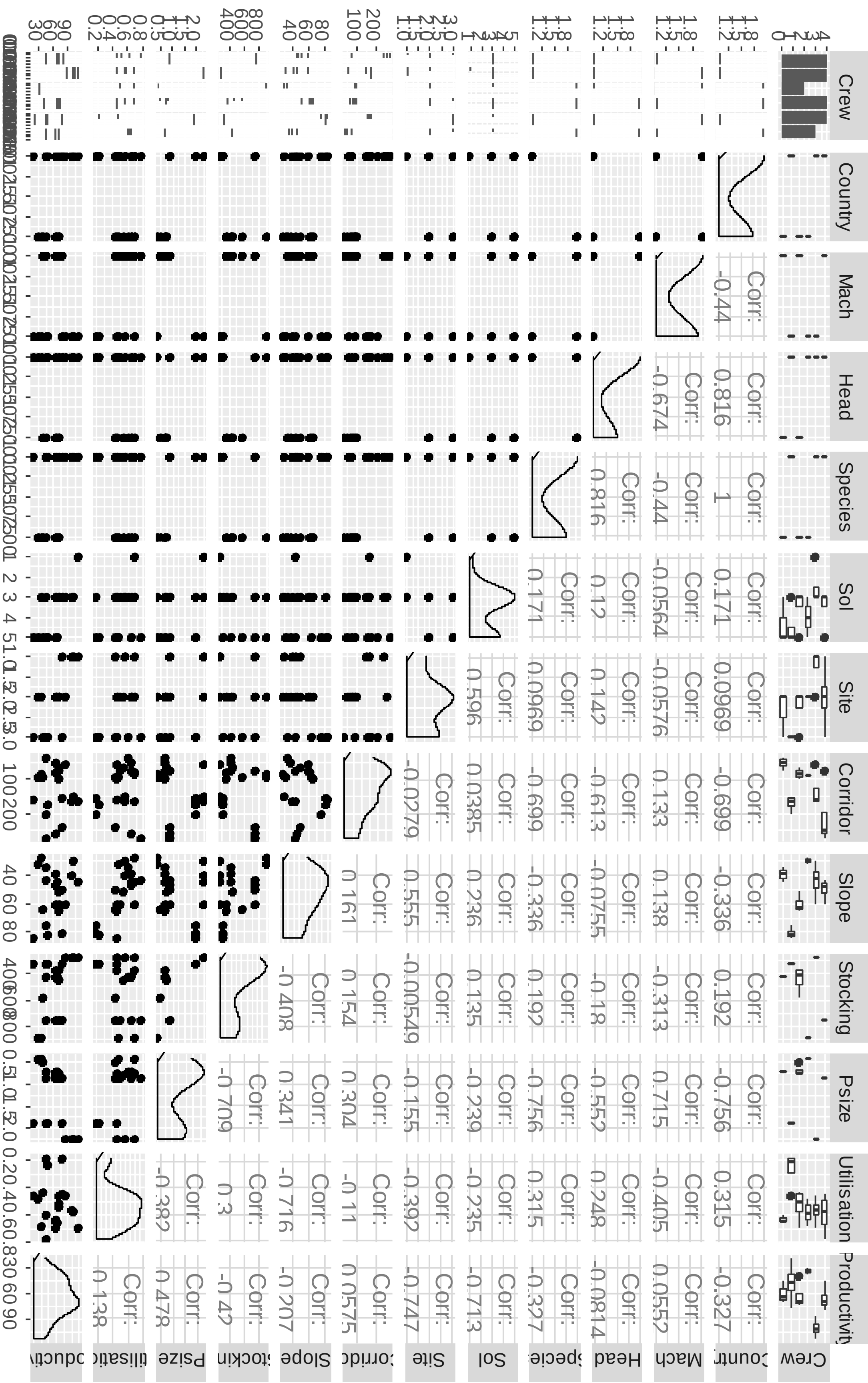
Appendix

Appendix 1: Full model and R output

1 NZ / 2 Canada	1 EX / 2 BD	1 Direct / 2 Hot	1 Mono / 2 Multi	Soil class	SD class	Average corridor (m)	Avg slope (%)	Stocking (SPH)	Piece size (m3)	Utilisation (%)	Productivity (m3/PMH)
1	1	1	1	5	3	270	44	757	0.88	77	45.1
1	1	1	1	3	2	255	47	757	0.88	64	67.7
1	1	1	1	3	1	240	50	757	0.88	44	80.3
1	1	1	1	3	2	75	60	757	0.88	51	71.8
1	2	1	1	1	1	166	45	278	2.23	69	113.3
1	2	1	1	3	1	166	40	278	2.23	56	99.8
1	2	1	1	3	1	148	30	278	2.23	57	102.2
1	2	1	1	3	2	55	60	278	2.23	45	86.9
1	2	1	1	5	3	201	75	320	1.9	18	45.6
1	2	1	1	5	3	171	82	320	1.9	23	49.2
1	2	1	1	5	3	157	84	320	1.9	46	19.7
1	2	1	1	3	3	155	81	320	1.9	18	77.9
2	1	2	2	5	2	75	45	423	0.7	66	70.1
2	1	2	2	5	2	51	39	423	0.7	64	64.7
2	1	2	2	3	3	37	35	423	0.7	60	46.3
2	1	2	2	5	3	92	64	575	0.5	44	41.0
2	1	2	2	3	2	100	65	368	0.74	45	73.1
2	1	2	2	3	2	80	61	368	0.74	70	67.2
2	1	2	2	3	2	65	51	450	0.79	54	72.4
2	2	1	2	3	2	87	28	890	0.41	69	37.4
2	2	1	2	5	2	93	32	890	0.41	48	30.6

R output


Crew
Country
Mach
Head
Species
Sol
Site
Corridor
Slope
Stocking
Psize
Utilisation

Appendix 2: Field measurement sheets

Date: ______ **University Of Canterbury** **Time Study#:** ______
Start: ______ **Forest Engineering Department** **Day#:** ________
Finish: ______ **Cameron Leslie Master's Thesis** **Crew:** ________

Operating Key:

W: Felling
M: Moving
S: Shovelling
OOS: Out of Sight

Delay Key:

OP: Operational
M: Mechanical
P: Personal

Working (felling, pre-bunching, delimbing, brushing)

Key	**Time**	**No. of trees**	**Comments**	**Key**	**Time**	**No. of trees**	**Comments**

University Of Canterbury

Forest Engineering Department

Cameron Leslie Master's Thesis

Operational Delay (>10 minutes)

________ Minutes Problem____

________ Minutes Problem____

________ Minutes Problem____

________ Minutes Problem____

________ Minutes Problem____

Mechanical Delay (>10 minutes)

________ Minutes Problem____

________ Minutes Problem____

________ Minutes Problem____

________ Minutes Problem____

________ Minutes Problem____

Personal Delay (>10 minutes)

________ Minutes Problem____

________ Minutes Problem____

________ Minutes Problem____

________ Minutes Problem____

________ Minutes Problem____

Comments:

University Of Canterbury

Forest Engineering Department

Cameron Leslie Master's Thesis

Time Study Observation Sheet

Soil Class: ____

Notes:

____

____

____

Site Difficulty: ____

Notes:

____

____

____

Terrain Assessment: ____

Notes:

____

____

____

Safety Practices:

____

____

____

____

____

____

Environmental Practices:

____

____

____

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____

____